# THE GEOLOGY OF THE SEA
# OF THE HEBRIDES

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## SUMMARY

Offshore shallow seismic, bathymetric and geological surveys are interpreted and, together with other geophysical data and onshore geology, used to produce a description of Quaternary and Pre-Quaternary geology. An attempt is then made to trace the geological evolution of the Sea of the Hebrides from the Late Palaeozoic to the present.

A major unconformity separates consolidated Pre-Quaternary rocks from unconsolidated Quaternary sediment. The Pre-Quaternary geology is controlled by three principal north-easterly faults which form the western margin of asymmetric troughs floored by Pre-Cambrian and probably Palaeozoic rocks and filled with Permo-Triassic to Cretaceous sediments. A third asymmetric trough has been detected on the outer continental shelf.

Tertiary igneous activity and north-westerly faulting are important secondary controls on the geology.

The Pre-Quaternary unconformity on the inner continental shelf has a characteristically glaciated morphology and patterns of ice movement can be deduced.

A Quaternary sequence, locally exceeding 250m in thickness, is divided into four sedimentary formations. These are interpreted as glacial moraine, glacial-marine sediment, peri-glacial marine sediment and modern sediment. The sequence was deposited

diachronously by the retreating ice of the last (Devensian) ice sheet. Concentration of glacial-marine sediment along the paths of major ice-sheets is considered to be responsible for the major variations in Quaternary sediment thickness. The complex morphology of the present sea floor reflects the Pre-Quaternary geology, glacial sedimentation and the present marine regime.

The complexity of the geology is such that this study must be regarded as a first reconnaissance.

# C H A P T E R 1

# I N T R O D U C T I O N

## 1.1. AREA AND OBJECTIVES

This study attempts to trace the geological evolution of the Sea of the Hebrides, western Scotland (Fig.1). Offshore shallow seismic, bathymetric and geological surveys are interpreted and integrated with the results of magnetic and gravity surveys and with the geology of the islands and mainland.

A major unconformity separating consolidated pre-Quaternary rocks from unconsolidated Quaternary sediments is recognised and provides a natural division for the study. Evidence for the offshore pre-Quaternary and Quaternary geology is presented and interpreted in chapters 2 and 3 respectively. From these interpretations and from onshore information the evolution of the area is traced from the late Palaeozoic through to the present.

By standards on land the scale is a reconnaissance one, but even at this level of detail the task is not simple. All pre-Quaternary systems are represented, commonly by a variety of rock types. Geophysical contrasts are often low and careful analysis of the results of a variety of techniques together with sampling and consideration of the land geology is necessary to produce a basic description. Variation in the resistance of pre-Quaternary rocks has caused differential erosion during the Quaternary and this in turn has resulted in a complex history of glacial and marine sedimentation.

Details of offshore surveys are given in Appendix 1.

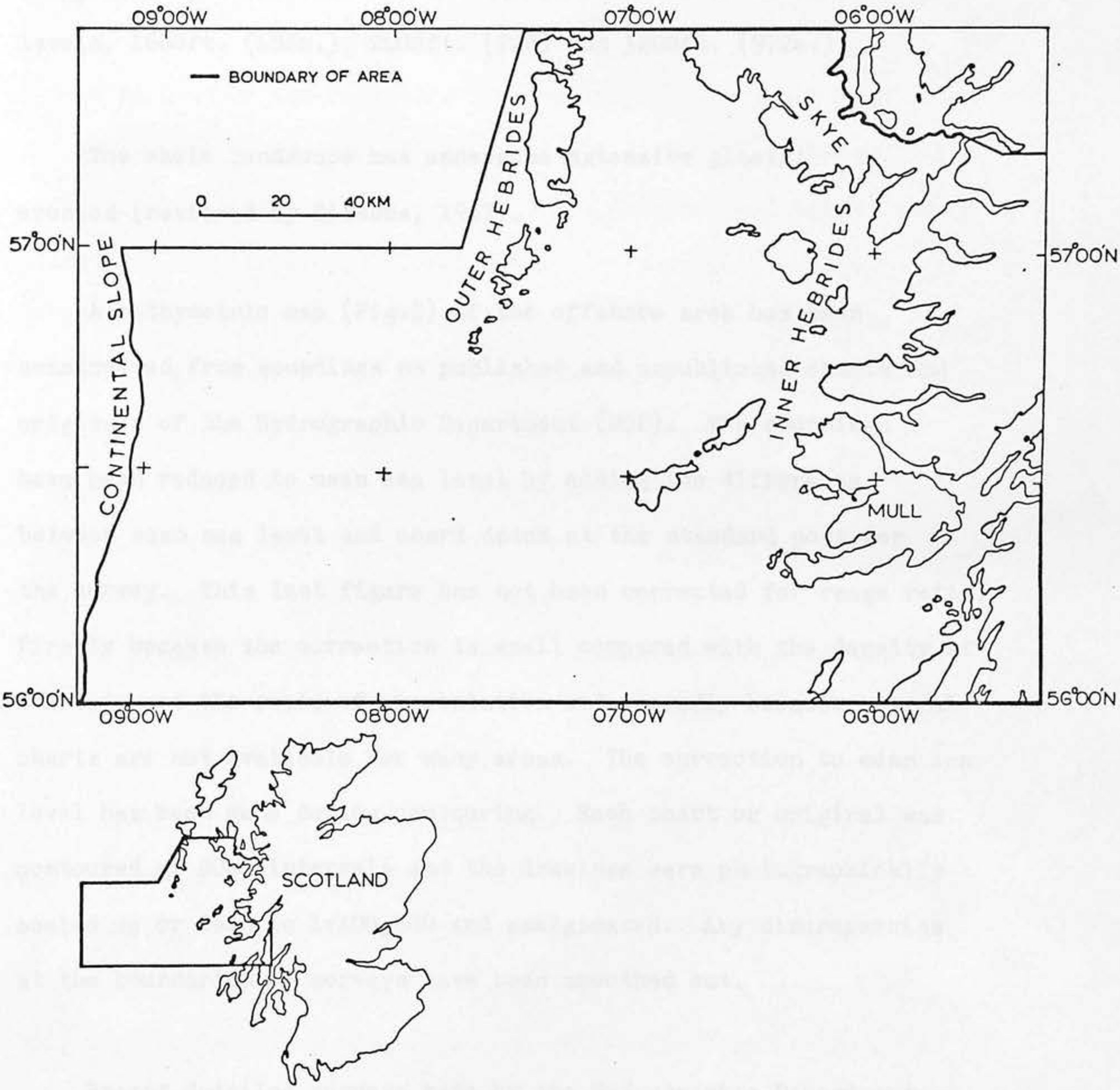



Fig.1. The Sea of the Hebrides.

## 1.2. TOPOGRAPHY AND BATHYMETRY

The onshore area has complex relief (Ordnance Survey 1:250,000 sheets 4 and 6). A fjord-dissected coastline separates the mainland from a continental shelf with two chains of islands, the Inner and Outer Hebrides (Fig.1). There are mountains rising to over 900m. both on the mainland and on the islands of the Inner Hebrides. George (1966) shows that the summits rise to one of three distinct levels, 1600ft. (486m.), 2400ft. (728) and 3200ft. (972m.).

The whole landscape has undergone extensive glacial erosion (reviewed by Sissons, 1967).

A bathymetric map (Fig.2) of the offshore area has been constructed from soundings on published and unpublished charts and originals of the Hydrographic Department (MOD). The soundings have been reduced to mean sea level by adding the difference between mean sea level and chart datum at the standard port for the survey. This last figure has not been corrected for range ratio, firstly because the correction is small compared with the density of the data and the scale of presentation and secondly because cotidal charts are not available for many areas. The correction to mean sea level has been made during contouring. Each chart or original was contoured at 20m. intervals and the drawings were photographically scaled up or down to 1:100,000 and amalgamated. Any discrepancies at the boundaries of surveys have been smoothed out.

Recent detailed surveys made by the Hydrographic Department cover much of the area of the main channel of the Sea of the Hebrides, the Little Minch, the Firth of Lorne and part of the shelf and slope west of Stanton Banks. Elsewhere published charts with a lower density of soundings have been supplemented locally by IGS echo-sounder data. In places the denser coverage results in a substantially different contour map than that published by Ting (1937, Map 1) and the following description draws attention to these.

A glaciated inner shelf extending westwards to Stanton Banks and the islands of the Outer Hebrides contrasts with a comparatively flat outer shelf. The top of the continental slope lies between 140m and 180m. Hydrographic Department surveys (K2706/1 and K5223) and an unpublished manuscript map (Roberts D.G., personal communication) indicate that it has a uniform gradient of 1 in 10 ($6^{o}$) down to 1200m. Here the slope between $56^{O}$N and $57^{O}$N is broken by the Hebrides Terrace Seamount (Roberts, 1971) which diverts the contours some seventy kilometres to the west. On the outer shelf there are four shallow depressions lower than the top of the continental slope. Stanton Banks together with the southern islands of the Outer Hebrides and the shoals south of these islands form the eastern margin of the outer shelf.

Although the coastline of the Outer Hebrides is embayed, two well defined trends are present on the east coast. From Berneray to Eriskay the coast has a rectilinear trend to the north-east. North of Eriskay it describes a regular curve which continues into the Minch. A longitudinal trench up to 275m deep, consisting of a series of hollows, runs parallel to the coast east of the Outer Hebrides; south of Eriskay a single channel parallels the coastline, but is broken by steep sided shoals offPabbay Island (cf Ting 1937, Map 1). It terminates as an enclosed depression south-east of Berneray Island. North of Eriskay this NE-SW channel is absent. A feature with this orientation is however formed by the ends of enclosed depressions which originate amongst shoal areas extending for some ten kilometres off the coast. Between Benbecula and Skye a broad depression again follows a north-easterly trend. An adjacent line of depressions runs south-westwards from Canna Island and converges with the main channel off Berneray.

The islands and shoals of the Inner Hebrides are dissected by enclosed depressions and the coastlines are embayed with fjords. A strong north-east to south-west trend is dominant in the Firth of Lorne area and is also evident further north on the coast of Skye, in the Sound of Sleat, between the islands of Rhum and Eigg, off the east coast of Coll and off the west coast of Ardnamurchan. In contrast the troughs north of Hawes Bank, Loch Sunart, Sound of Arisaig and Loch Morar trend from east to west, and the Sound of Mull from south-east to north-west.

In the south an even sea floor is broken by rock shoals, the largest of which form Stanton Banks and the Blackstone Bank.

## 1.3. SUMMARY OF ONSHORE GEOLOGY AND PREVIOUS OFFSHORE WORK

The geology of the Western Highlands and Islands of Scotland is complex, the area was deeply eroded during late Tertiary and Pleistocene times and a great variety of rock types is now exposed.

This section briefly describes the geology of the adjoining mainland and islands (Fig.3) and reviews previous offshore work.

## 1.3.1. Pre-Cambrian to Middle Tertiary

A Caledonian thrust belt separates a foreland group consisting of late pre-Cambrian (Torridonian) and Cambro-Ordovician unmetamorphosed sediments resting on pre-Cambrian Lewisian gneisses to the west, from a metamorphosed group of mainly psammitic schists (Moine) to the east (Phemister 1960, p55). North of Skye the thrust belt crops out on the mainland and trends south-south-west to cross the coast onto Skye. South of Skye the thrusts themselves are not seen, but the position of the uppermost (Moine) thrust has been traced between the respective positions of foreland and the schist groups.

West of this thrust belt the foreland group forms a basement upon which later formations have been deposited. Both Lewisian and Torridonian rocks crop out on most of the islands of the Hebrides, and Lewisian rocks form the islands of Coll and Tiree and those islands of the Outer Hebrides within this area. To the east of the Moine Thrust the Moine Schists form a metamorphic basement, together with a second group of Caledonian metasediments, the Dalradian.

Devonian conglomerates, sandstones, shales and lavas rest unconformably on Dalradian schists on Lorne and at least 12m of Carboniferous sandstones with shale beds and one coal seam occur on Morven (Johnstone 1966, p69; Lee and Bailey 1925, p22, p56).

Hercynian stresses produced major NE-SW wrench faults including the Great Glen and Strathconan faults (Kennedy, 1946). Kennedy estimates sinistral movement on the Great Glen Fault to be of the order of 100km.

In the Inner Hebrides Mesozoic sediments, lying unconformably on earlier formations, have been protected from erosion by overlying Tertiary lavas (Richey and others, 1961 p20), the main outcrops being on Skye, Raasay and Mull with smaller ones on the other islands of the Inner Hebrides and on the mainland. The succession varies with locality but an overall pattern can be recognised. Red beds of Permo-Triassic age are preserved in down-faulted basins and hollows in older rocks and pass conformably upwards into Jurassic marine sediments some 900m thick. Upper Cretaceous marine sediments up to 20m thick rest unconformably on an eroded Jurassic surface and overstep older formations. To the south-east of the Camasunary Fault on southern Skye Mesozoic sediments were downthrown at least 650m against Torridonian sandstones (Peach and others, 1910 p150). Pre-Cretaceous movement on the fault is strongly suggested by the presence of Upper Cretaceous sediments resting on Lias, west of the fault, and Upper Jurassic east of the fault. Separation of the outcrops is however great enough to allow the possibility of overstep prior to faulting. The fault is a major structure which can be traced both northwards across the island of Raasay and southwards where Peach and others (1910) suggested that it ran east of the islands of Rhum (Torridonian) and Coll (Lewisian) but west of the Mesozoic outcrops on Eigg Island and the Ardnamurchan peninsula.

In places a thin basal Tertiary sequence of conglomerates, sandstones and lignites of Eocene age rests on older rocks and passes upwards into a persistent mudstone. The sequence is best seen in Mull where it is up to 6m thick (Bailey and others 1924, p53).

Here the sedimentary sequence ends and the base of a thick pile of Eocene basaltic lavas marks the start of a major episode of volcanic activity (Richey and others, 1961, p41), though on northern Skye tuffs intervene between sediments and lavas (Anderson and Dunham, 1966, p73). Intrusive complexes on Skye, Mull, Rhum and the Ardnamurchan peninsula represent a younger expression of the igneous activity. McQuillin and Tuson (1963) and Bott and Tuson (1973) have shown centres to be underlain by basic and ultrabasic rocks extending to a depth of 14-15km. They are broadly contemporaneous with the emplacement of NW-SE dyke swarms which are associated in places with NW-SE faults which on Skye have maximum throws of about 400m. Tertiary (post-lava) movement on the Raasay Fault is suggested by the evidence of lavas on the south-east of the fault lying at a lower level than Torridonian rocks to the north-west.

Two papers have suggested Tertiary dextral movement on the Great Glen Fault (Holgate, 1969; Garson and Plant, 1972).

Previous writers have looked to the bathymetry of the area for evidence of major geological structure. In particular, attention has centred on the main channel of the Sea of the Hebrides and the scarp which forms its western margin. Mackinder (1907, p75) was first to propose that it represented a submerged rift valley and this suggestion was taken up by others (reviewed by George, 1966, p16). George pointed out the absence of any evidence of an eastern margin to the rift and favoured the explanation that the elongated troughs mark a fault line. The suggestion of a major fault in the Minch, made by Ting (1937, p79) and Holtedahl (1952, p219) was later taken up by Dearnley (1962) who explained the discordance of structural zones in the Lewisian of the mainland and the Outer Hebrides by sinistral movement on a Minch Fault; this fault being analogous to the Great Glen Fault. All three writers also noted the trenches on the east side of Coll and Tiree and suggested that these may represent the continuation of the Strathconan Fault.

Dykes on Islay and Jura appear to be centred on a plutonic centre to the north-west of Islay (McCallien, 1932, p51). Such a centre has since been confirmed by geophysical evidence (Bullerwell, 1963, p67 and 1972, p211; Roberts, 1970).

Recent offshore work is reported by Eden and others (1971), Smythe and others (1972), Eden and others (1973), McQuillin and Binns (1973) and Binns and others (1974a). A discussion on the area is given by Hall and Smythe (1973) in reply to Hallam (1972).

### 1.3.2. Middle Tertiary to the present

During late Tertiary and Pleistocene times the area was extensively eroded and considerable thicknesses of rock were removed to uncover Tertiary plutonic complexes; in addition a pulsed emergence of the land is indicated by the remains of plateaux and benches at various levels (George, 1966; Sissons, 1967, p15). No late Tertiary deposits have been reported and most Pleistocene interglacial deposits are assumed to have been eroded during the last glaciation; those that remain are isolated and have not been correlated with the glacial-interglacial sequence present in England (West, 1968, p235). Locally raised cliff lines eroded by ice are believed to mark interglacial shores.

Most erosional and depositional evidence remaining today relates to the last (Devensian) ice age. Erosional land forms are dominantly glacial; boulder clay covers much of the lower ground and outwash fans and other fluvio-glacial deposits are common.

Striae and erratic boulders indicate the east to west movement of an ice sheet across the area. The ice originated in the Western Highlands and spread radially out across Scotland and the Hebridean islands. Locally the ice was deflected by high ground in Mull, Rhum and Skye, and ice from these centres formed valley glaciers as the main ice sheet decayed. Erratics found in the Outer Hebrides include Cretaceous chalk, Triassic sandstones and Carboniferous limestone (Jehu and Craig, 1923, p440 and 1925, p639) suggesting that these formations may form part of the sea floor to the east.

Following the last glaciation the decay of the ice was interrupted by three 'late glacial' readvances (Sissons, 1967, p125). The land, relieved of the weight of the ice, rose and at the same time world wide de-glaciation resulted in a eustatic rise in sea level. Close to the centre of the ice sheet, uplift was at a maximum and remnants of the late glacial shorelines are found some 25-30m above present sea level; in places these are associated with outwash fans. Younger shorelines, including a well defined Post-glacial one, (the '25ft. bench') occur at lower levels.

The amount of isostatic uplift decreased away from the Western Highlands resulting in an inclination of the older beaches. Although the evidence for this is clearest on the eastern side of the Grampians, evidence from Ireland and from the coast northwards from Mull indicates that the same process has occurred on the west coast (Synge and Stephens, 1966; Sissons, 1967 p170, p199). This is consistent with evidence of the recent submergence of the Outer Hebrides, where isostatic uplift has failed overall to exceed eustatic rise in sea level.

The history, however, is not simple. At the end of late glacial times isostatic uplift throughout the area exceeded the eustatic rise in world sea level and relative sea level fell to near the present position, permitting the growth of peat. As isostatic uplift slowed sea level rose again, inundating the peat and culminating in a prominent Post-Glacial shoreline some 8m above present sea level in Mull and Lorne. Isostatic readjustment continued, lowering the shoreline to its present level and recent evidence shows that parts of the Scottish mainland are still rising slowly (Sissons, 1967, p213).

Recent offshore work is reported in Eden and others (1971 and 1973) and Binns and others (1974a and 1974b).

## 1.4. NAVIGATION

Four navigation methods have been used to position the surveys, Decca Hifix, Decca Main Chain, Radar and the sextant. The method used on each survey is listed in the survey report (Appendix 1).

Detailed Admiralty surveys (navigated by Decca Hifix at a scale of 1:50,000) cover most of the area and, as the density of IGS survey lines was too low to map the uneven topography of the sea-floor, these were used. In order therefore to ensure that maps of isobaths on rockhead and isopachytes on drift were consistent with bathymetry it was necessary to reposition some lines navigated by Decca Main Chain and Radar. Echosounder readings from these lines were plotted at a scale of 1:100,000 and the lines adjusted until the profiles best fitted the reduced Admiralty data (Shepard, 1963).

In areas where no detailed Hydrographic Department data exist, or in areas of even sea floor this could not be done. In such areas positioning discrepancies between lines have been noted and the possibility of discrepancies was considered when geological boundaries were being drawn.

# C H A P T E R 2

# D E S C R I P T I O N  O F  P R E-Q U A T E R N A R Y G E O L O G Y

## 2.1. EVIDENCE AND METHOD OF INTERPRETATION

A great variety of lithologies, ranging in age from Pre-Cambrian to Tertiary are exposed on the coasts and islands of west Scotland and may therefore be expected offshore. Offshore interpretation is made in three stages. Firstly raw data from a number of geophysical techniques are interpreted and presented on maps; secondly areas having similar combinations of geophysical characteristics ('geophysical domains') are mapped out; thirdly a geological interpretation of the domains is made taking into account onshore geology, offshore regional structure (as deduced from deep seismic reflection profiles) and offshore sampling.

The physical similarity between many of the west Scottish rocks makes it essential to use a variety of geophysical techniques to detect contrasts. Even when this is done differences remain undetected; Torridonian sandstones for example are physically similar to indurated Palaeozoic sandstones; a Caledonian granite may be physically similar to a Lewisian granite; the presence of Tertiary basic igneous intrusions into Mesozoic sediments may give the latter a degree of resistance and a magnetic character similar to a Lewisian gneiss. In such cases, when interpreting a 'domain', it is necessary to take samples or to consider the land geology and the regional structure.

The evidence considered in this interpretation is as follows:-

2.1.1. Geophysical evidence

Aeromagnetic total-force anomaly map. Sheets 10 and 12 of the aeromagnetic map of Great Britain and Northern Ireland, National Grid Diagram Addition, scale 1:250,000. A summary map and a description by R.McQuillin is given in Binns and others (1974a, Fig4).

Bouguer anomaly gravity map. This map has been prepared by the Marine Geophysics Unit of the Institute of Geological Sciences. (McQuillin and Binns, 1973; Binns and others, 1974a). A description by R.McQuillin is given in these publications and the unpublished results of a recent survey west of Colonsay (McQuillin, personal communication) are also considered here.

Shipborne magnetometer profiles. Shipborne magnetometer results are not used to produce a magnetic anomaly map; the magnetograms have been used in conjunction with shallow seismic profiles to define precise relationships between magnetic deflections and structural features and to locate the position of geological boundaries. The results are also used in mapping and identifying geophysical domains and are summarised in Table 1.

Shallow seismic reflection profiles. Shallow seismic profiles aid interpretation in two ways:

(i) On shallow seismic profiles over the inner continental shelf a major acoustic reflector, coincident with a stratigraphic unconformity, is interpreted as a rockhead reflection. The morphology of this surface is characteristically glaciated and cores taken from stratigraphically high in the sediment sequence below the unconformity are of Mesozoic sediment (SH 133 and SH 177, Appendix 2). The rocks below this unconformity are interpreted therefore as being Pre-Quaternary in age.

Together with bathymetric evidence the profiles have been used to map out the regional morphology of rockhead (Fig.4). This can be expected to reflect lithology and is therefore important evidence. Depths to the rockhead reflector are calculated by adding water depth to sediment thickness and interpolation of isobaths between seismic profiles is based on the cover of bathymetric data which is denser than that from the seismic profiles. The coincidence of prominent features on the sea-floor and structural and lithological changes deduced from geophysical evidence allows many boundaries to be interpolated from bathymetric evidence.

(ii) The profiles provided information about the character of the Pre-Quaternary rocks. Structure, in the form of bedding, dislocation and faulting is shown; apparent dips have been calculated assuming a seismic velocity of 3.048km/sec; at cross-overs true dips have been calculated; the character of bedding has also been considered.

Where structure is absent the character of the rockhead surface is evidence for lithology. It is useful to distinguish three types of rockhead surface; a topographically high, uneven surface is characteristic of many crystalline rocks; a topographically low, smooth surface is characteristic of Mesozoic sediments. The remaining surfaces, which are gradational between these two, form the third group. It is not practical to define quantitatively the terms smooth and 'uneven' instead definition is by reference to type examples (Figs.6-8). A summary of the shallow seismic evidence is mapped out in Fig.5.

Deep seismic reflection profiles. This survey was run, and a preliminary interpretation for I.G.S. made by Seismograph Service Ltd. (Seismograph Service Ltd., 1970). Here the main features of this interpretation are accepted although errors in picking have been noted.

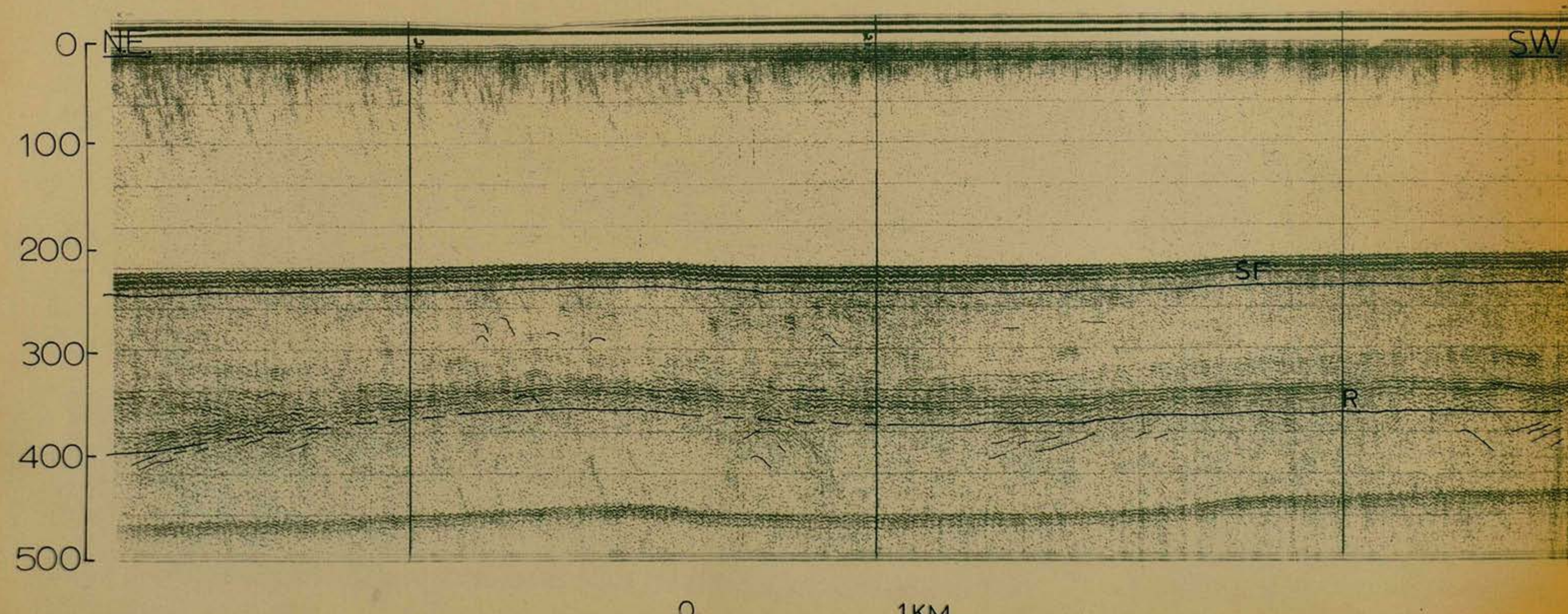



Fig.6. Shallow seismic profile - rockhead smooth and topographically low. Note also structureless texture of Quaternary (Formation 2c) sediments above rockhead. For location see Figs.5 or 26. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds.

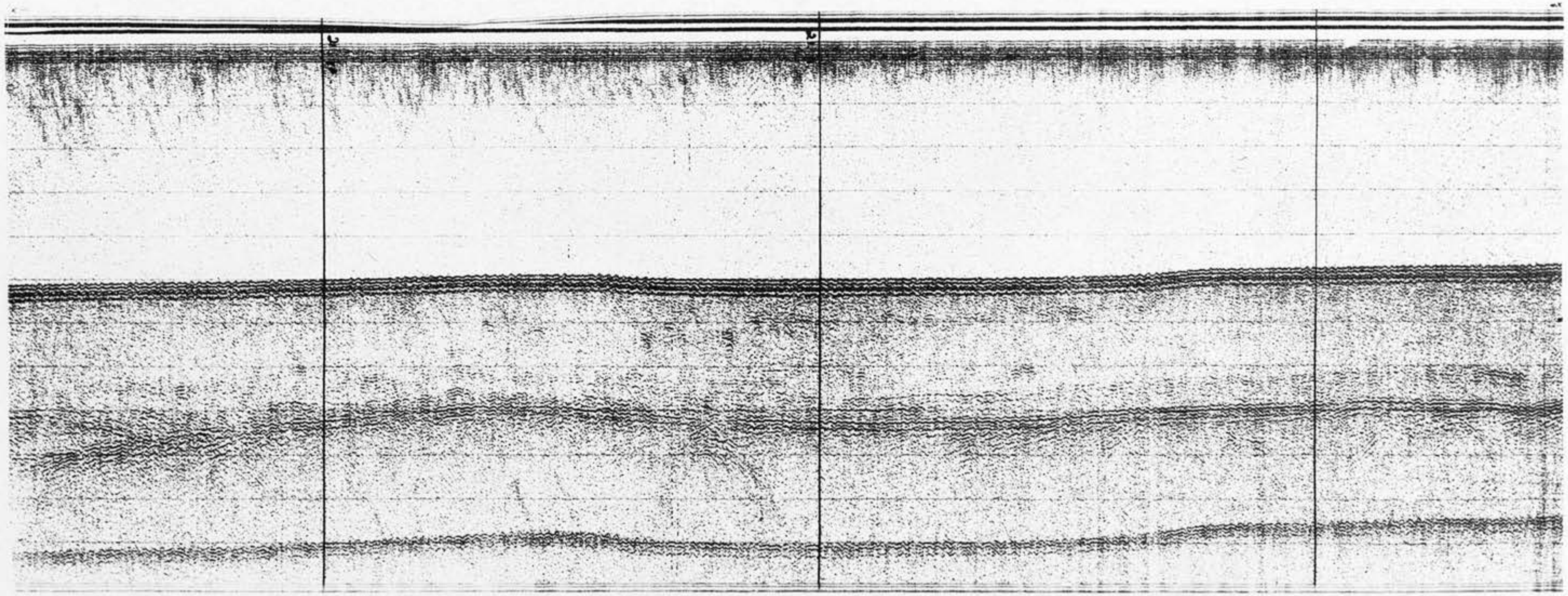


Fig.6. Shallow seismic profile - rockhead smooth and topographically low. Note also structureless texture of Quaternary (Formation 2c) sediments above rockhead. For location see Figs.5 or 26. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds.

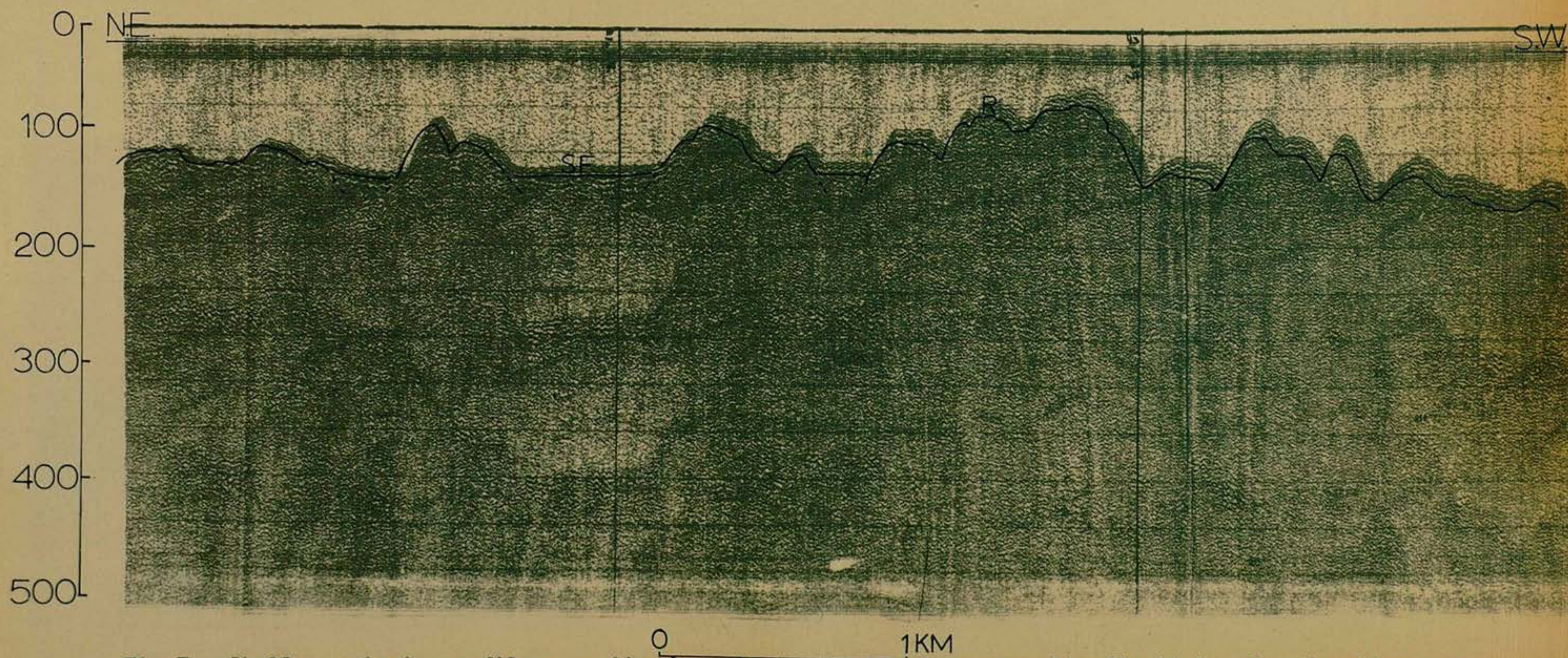



Fig.7. Shallow seismic profile - rockhead surface uneven and topographically high. For location see Fig.5. SF - Sea floor; R - Rockhead; Vertical scale - two-way time in milliseconds.

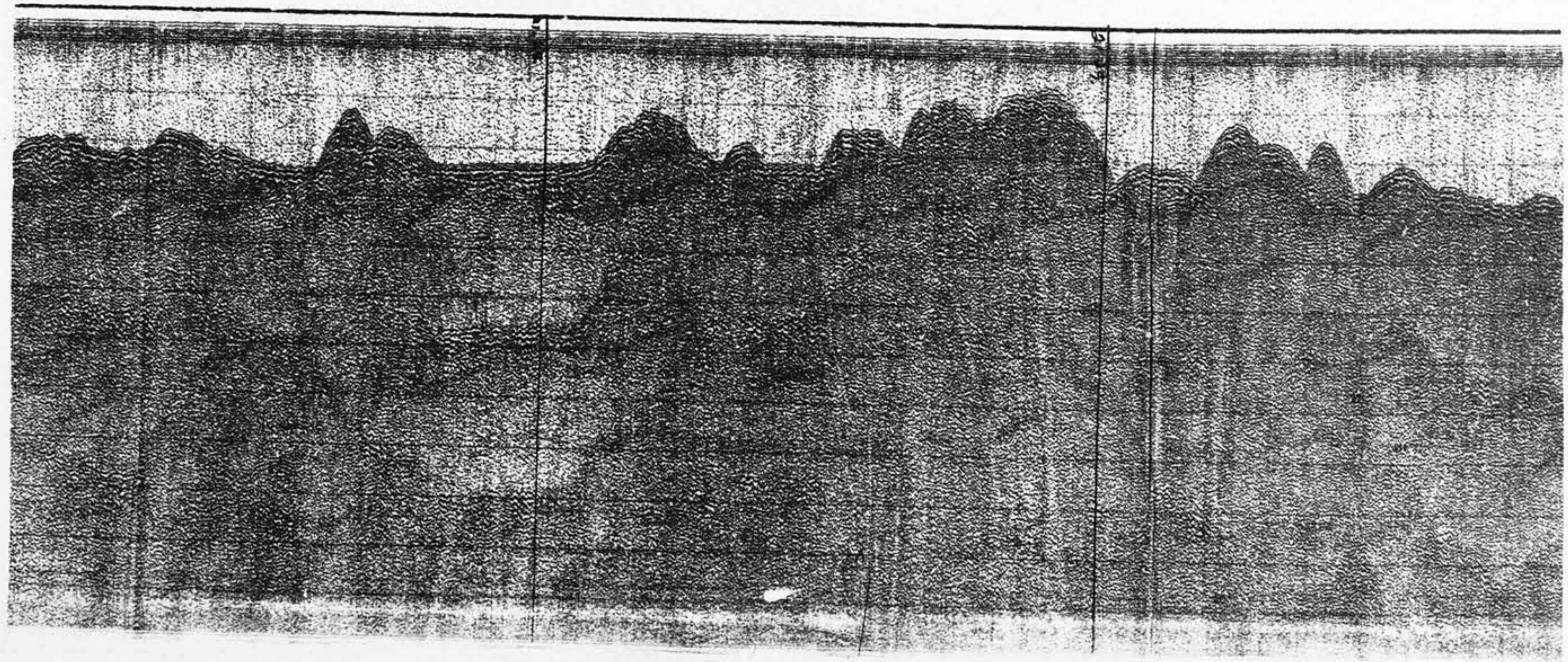


Fig.7. Shallow seismic profile - rockhead surface uneven and topographically high. For location see Fig.5. SF - Sea floor; R - Rockhead; Vertical scale - two-way time in milliseconds.

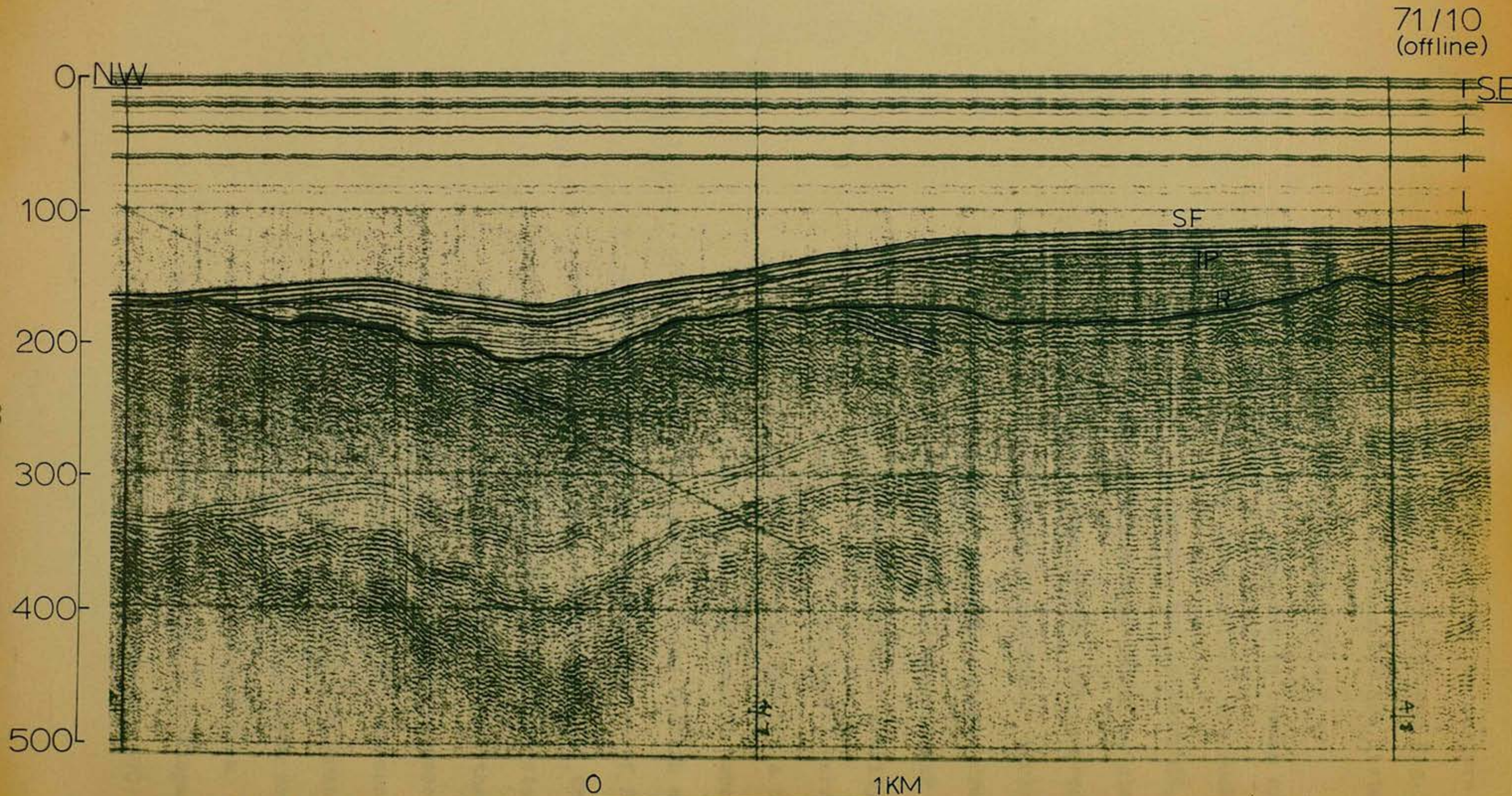



Fig. 8. Shallow seismic profile - rockhead surface undifferentiated. Note also well-bedded Quaternary (Formation 3) sediments lying above rockhead. For location see Figs. 5 or 26. SF - Sea-floor; IP - Base of initial pulse; R - Rockhead; Vertical scale - two-way time in milliseconds.

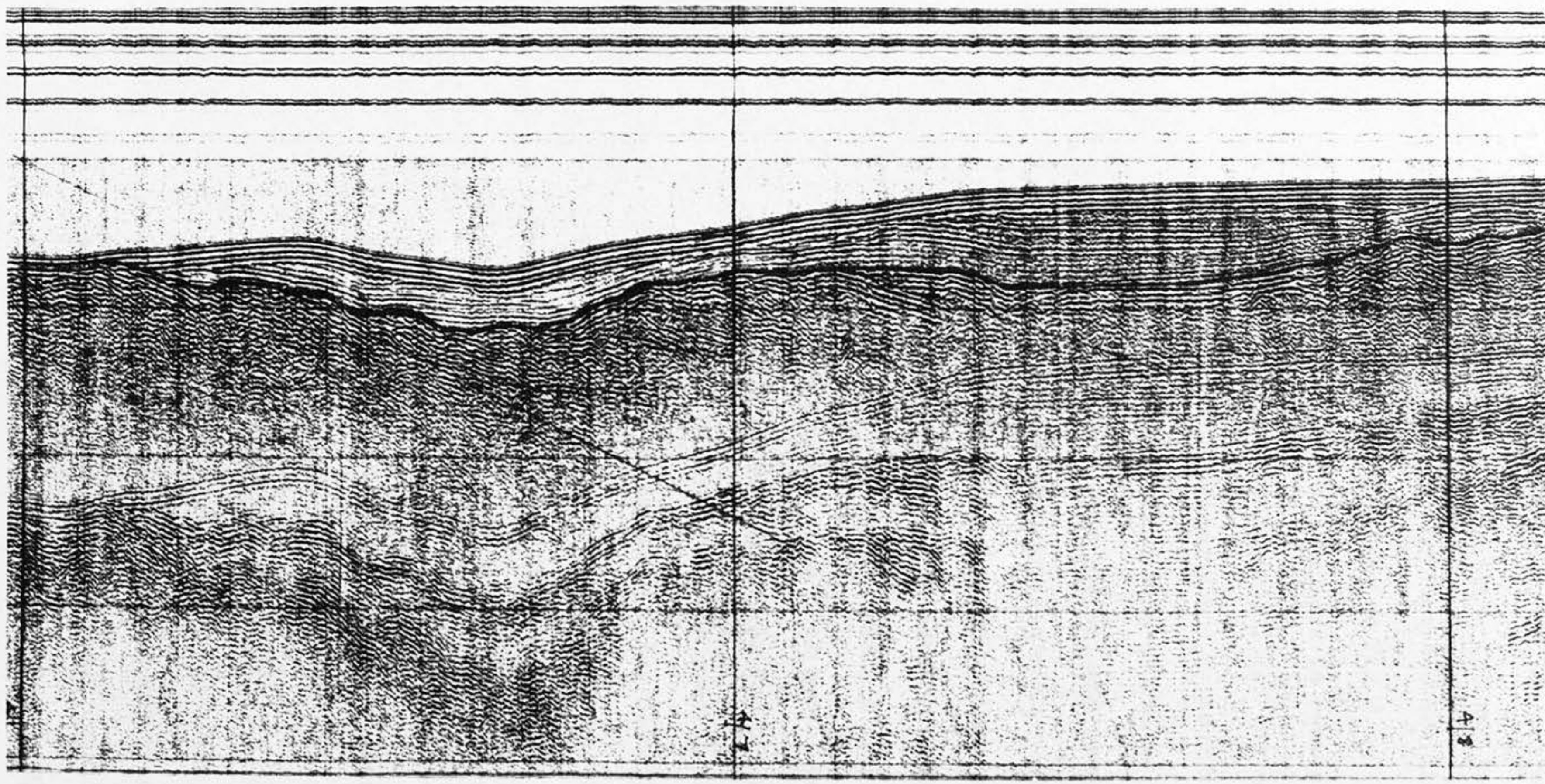



Fig. 8. Shallow seismic profile - rockhead surface undifferentiated. Note also well-bedded Quaternary (Formation 3) sediments lying above rockhead. For location see Figs. 5 or 26. SF - Sea-floor; IP - Base of initial pulse; R - Rockhead; Vertical scale - two-way time in milliseconds.

## 2.1.2. Geological evidence.

Onshore Geology. A summary of the onshore geology is given in the introduction (p6 and Fig.3).

Offshore sampling. Rock samples are listed in Appendix 2 and plotted on Fig.9.

Although sea floor exposure is common and often extensive (Eden and others, 1971) the rock exposed is mostly igneous and metamorphic, extremely resistant and worn smooth by glaciation. Softer rocks have been eroded, and covered by unconsolidated Quaternary sediment. Early attempts at sampling sea-floor outcrop, using a dredge, yielded only erratics with no single rock type predominating. Recoveries using a gravity corer fitted with a heavy steel rock barrel were poor and the possibility that the corer had hit a boulder could not be discounted. The gravity corer samples listed in Appendix 2 lay beneath a thin cover of superficial sediment and are of friable rock, unlikely to have survived glacial transport. Although there is some doubt about the status of these samples they form, together with the geophysical records, contributary evidence for the interpretation advanced in this account.

Light, cable-controlled drills with mounted underwater television cameras have been more successful in recovering solid rock from glaciated surfaces. During their development, the Harrison Drill (Eden and others, 1970) and the IGS "Midi Drill" (Eden and Ardus, 1972) have both recovered samples.

Five samples have been taken by the submersible Vickers Pisces; three using a manipulating arm or claw to pick out weathered-out blocks and two using a Harrison Drill attached to a torpedo-recovery claw (Eden and others, 1971, Eden and others, 1973).

In water up to 35m deep, particularly where rock exposure is rugged, Scuba diving has proved the quickest and surest method of recovering samples. The procedure has been for the shoal to be located and buoyed, and for divers, attended by an inflatable, to descend the buoy rope and recover samples (Eden and Binns, 1973).

Ten boreholes have been drilled by M.V. Whitethorn to recover cores of pre-Quaternary rock.

Thirty five geophysical domains have been mapped out (Fig.9). The geophysical characteristics of each of these are listed in Table 1 together with an interpretation. It should be noted that many domains have not been sampled, interpretation is therefore based only on seismic character and surface morphology. In these cases a wide range of possible ages has been assigned.

## 2.2. DESCRIPTION

### 2.2.1. Outline of main structures and formations.

The evidence listed above is now interpreted. It shows that three major faults are the primary controls on the geology (Fig.3). The Minch Fault and the Camasunary-Skerryvore Fault form the western margins of asymmetric troughs (the Sea of the Hebrides Trough and the Inner Hebrides Trough). They throw down Pre-Cambrian and possibly Palaeozoic rocks which floor the troughs and rise south-eastwards to appear from beneath infilling Mesozoic sediments. The Great Glen Fault, which on Mull may have moved normally down to the south east between the Jurassic and the Upper Cretaceous, downthrows sediments to the south-east offshore. There is also evidence for a fourth fault-bounded trough west of the Outer Hebrides (the Outer Hebrides Trough).

Tertiary igneous activity and NW-SE faulting have been superimposed on these structures. The faulting; which succeeded the igneous activity, in places raised the westward-tilting basement blocks and displaced their outcrop.

### 2.2.2. Area west of the Minch Fault.

Rockhead is not seen on shallow seismic records over Domains 29 and X1 (Fig.9), it falls seawards (Fig.4) and is overlain by a thickening sequence of Pleistocene and possibly Tertiary sediments. This situation is similar to those described north-west of St. Kilda

(Stride and others, 1969) and west of Shetland (Watts, 1971). The western limit of outcropping rockhead, however, lies some 60km from the continental slope in the present area compared with about 40km at St. Kilda and west of the Shetlands.

Nine geophysical domains are recognised west of the Minch Fault (Fig.9, Table 1).

The Minch Fault, together with the fault forming the eastern margin of the Outer Hebrides Trough, bound a basement block of two Lewisian domains, 28a and 30. A "Permian to Lower Jurassic" domain, 12a, lies to the east of the Lewisian outcrop off South Uist and Benbecula. Here a deep reflection profile (Seismograph Service Ltd., 1970) shows 650 msec. of sedimentary rock lying above a basal horizon interpreted here as a Lewisian surface. Carboniferous erratics on South Uist (Jehu and Craig, 1925) suggest that Domain 12a may include Carboniferous sediments also. The nature of the Lewisian-New Red Sandstone boundary is uncertain; a scarp in rockhead between 60m and 120m has been interpreted as the edge of the Lewisian. This is not rectilinear and the boundary is therefore assumed to be an unconformity. To the north, in the Minch, however it is, in part at least, faulted (D. A. Ardus, personal communication).

Two shoaler areas of uneven rock (Domain 4b) are interpreted as Tertiary basic hypabyssal rock, probably intruded through the Minch Fault.

The fault which forms the eastern margin of the Outer Hebrides

Trough (Domains 16 and 17) is based on gravity evidence. A gravity gradient coincides with a scarp in rockhead and to the west less resistant rocks are associated with lower gravity values and an absence of magnetic anomalies (Fig.10).

The sedimentary rocks of the Outer Hebrides Trough are structureless; their surface is even or locally uneven. The gravity map indicates the trough is asymmetric; a deeper, eastern section is defined by the 50mgal isogal. The age of these sediments is uncertain. The gravity anomalies associated with them suggest (by comparison with the other troughs) that the rocks are low in the sedimentary sequence: this is consistent with the absence of bedding which indicates that no Jurassic rocks are present (see discussion on the Sea of the Hebrides Trough below). The sediments have been assigned tentatively an upper Palaeozoic to Triassic age.

In Domain 29 a gravity high, >60 mgal, suggests the presence of Lewisian gneisses to the west of the trough.

In two domains, X1 and X2 there is not sufficient evidence to make an interpretation. The inclusion of most of the area of these domains within the 55 mgal isogal suggests the presence of Pre-Cambrian or Palaeozoic rocks.

### 2.2.3. Minch Fault to the Camasunary - Skerryvore Fault.

The location of the Minch Fault. Between Skye and Benbecula the fault, which continues northwards into the Minch lies close to the Outer

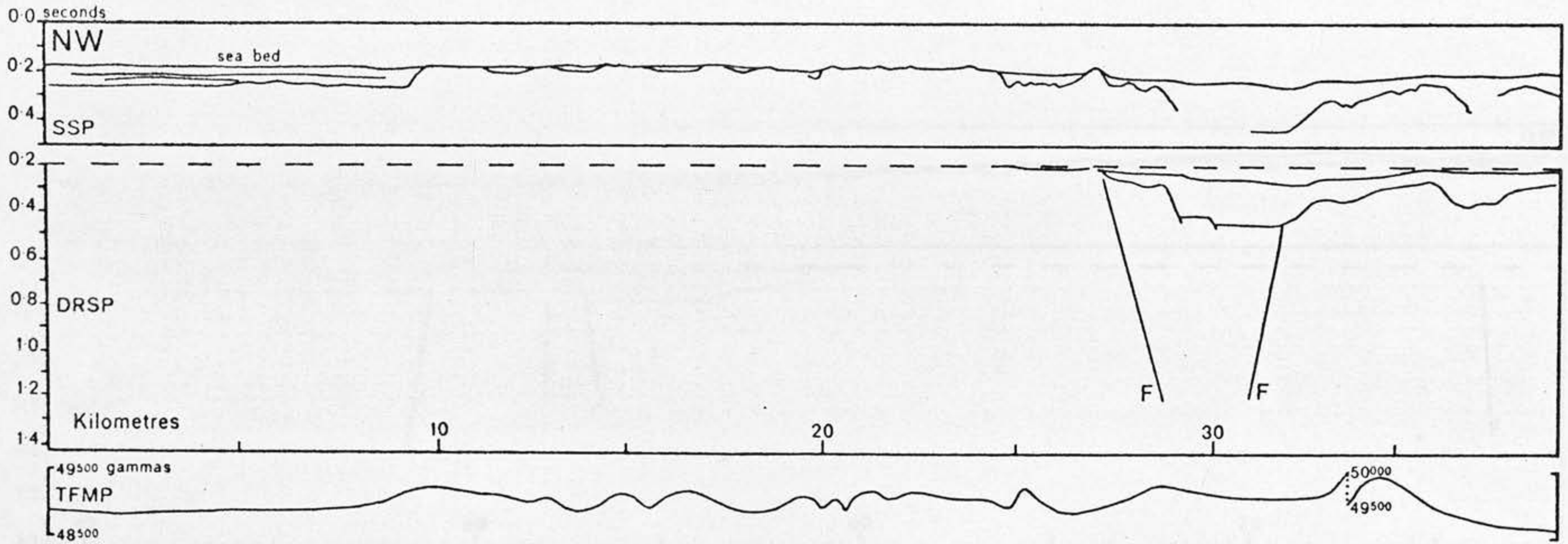



Fig.10a. Section A-A$^1$: shallow and deep reflection and shipborne magnetometer profiles. For location see Fig.3. From Binns and others, 1974a.

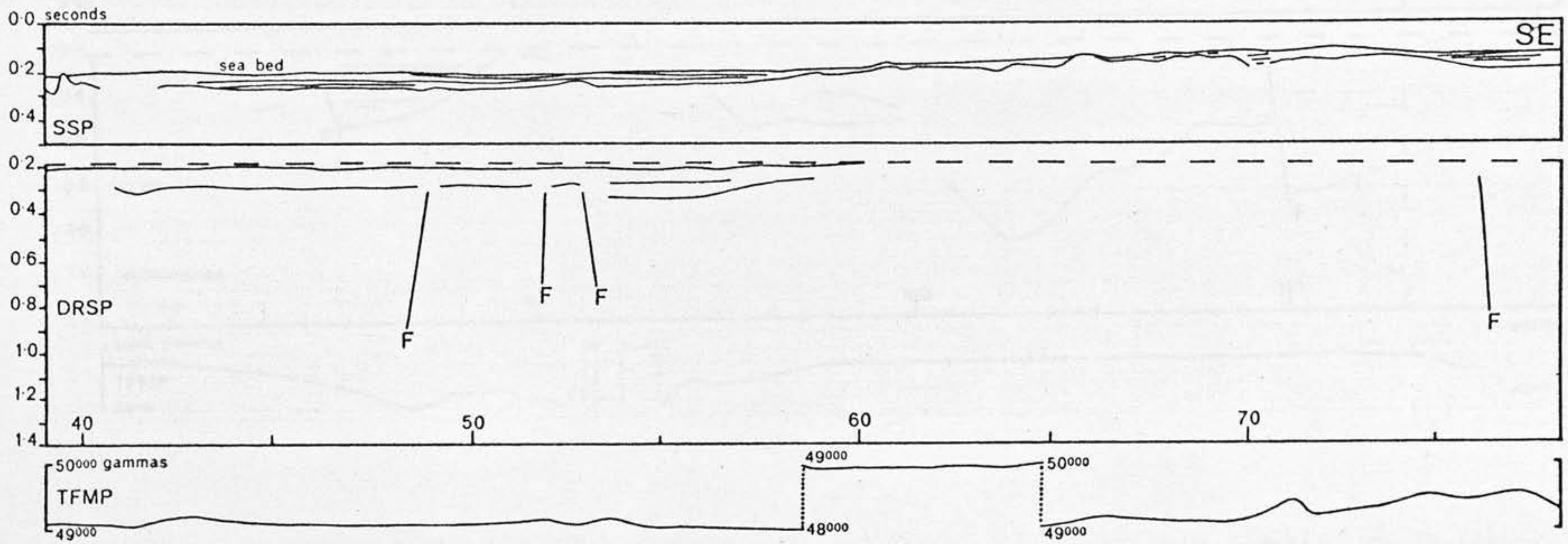



Fig.10b. Section A-A': shallow and deep reflection and shipborne magnetometer profiles. For location see Fig.3. From Binns and others, 1974a.

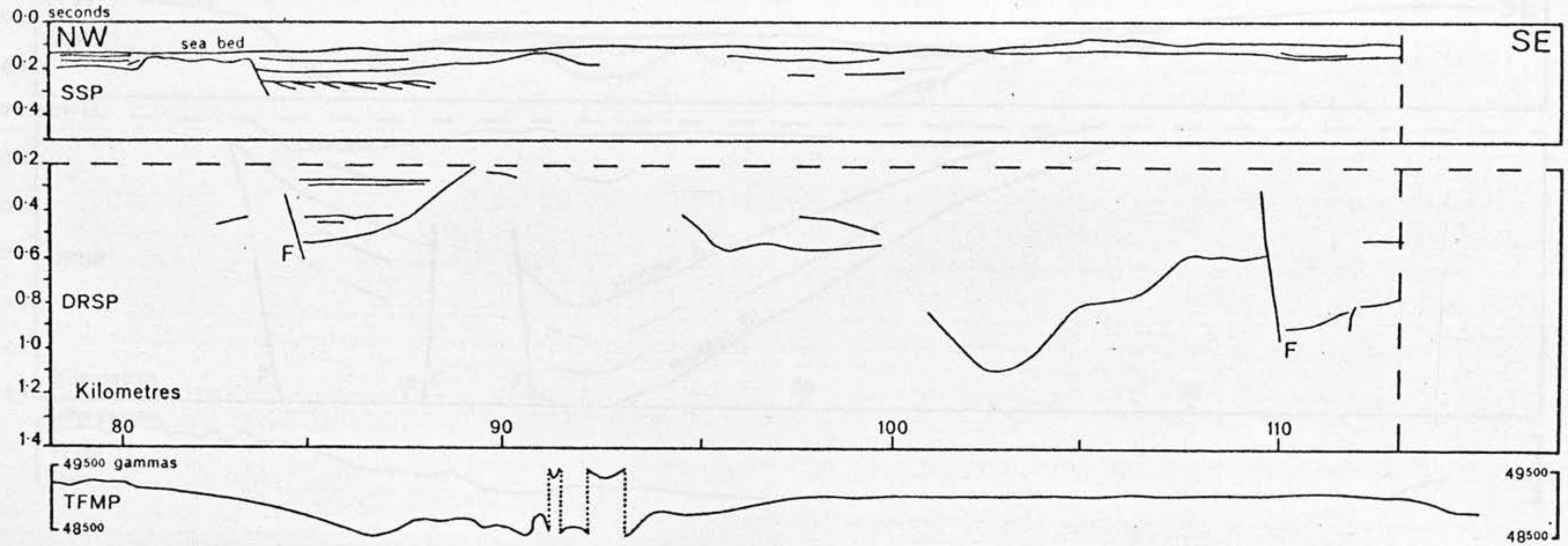



Fig.10c. Section A-A': shallow and deep reflection and shipborne magnetometer profiles. For location see Fig.3. From Binns and others, 1974a.

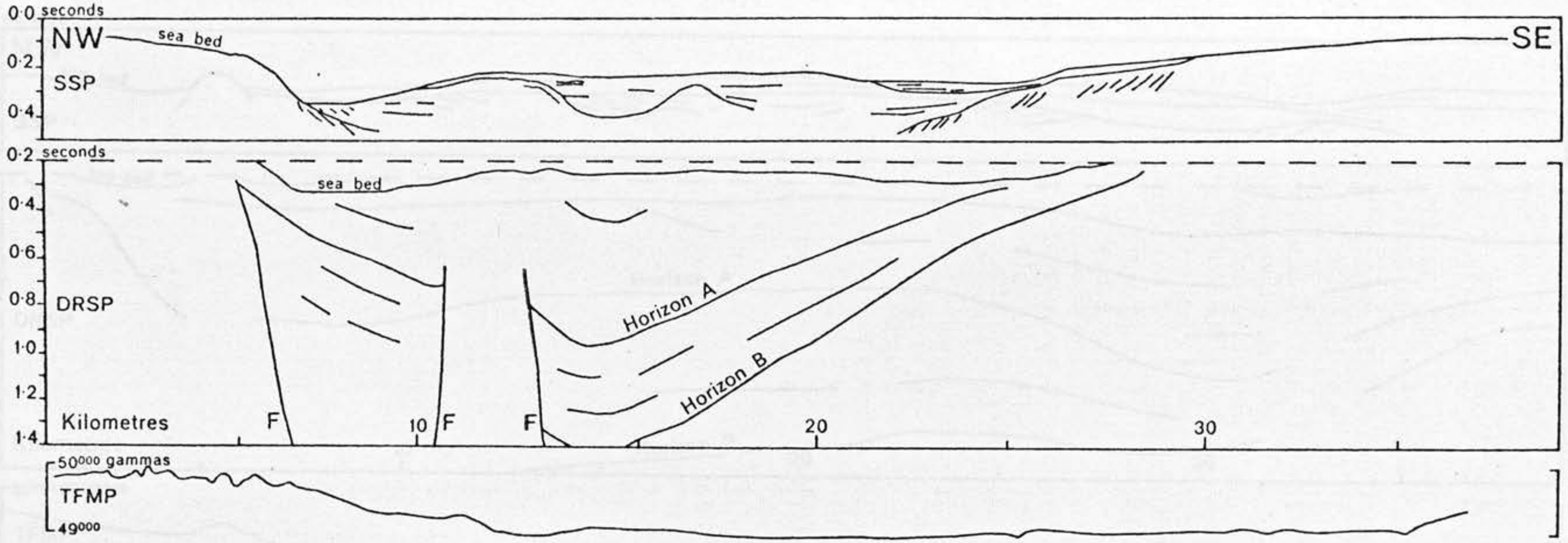



Fig.11. Section B-B': shallow and deep reflection and shipborne magnetometer profiles. For location see Fig.3. From Binns and others, 1974a.

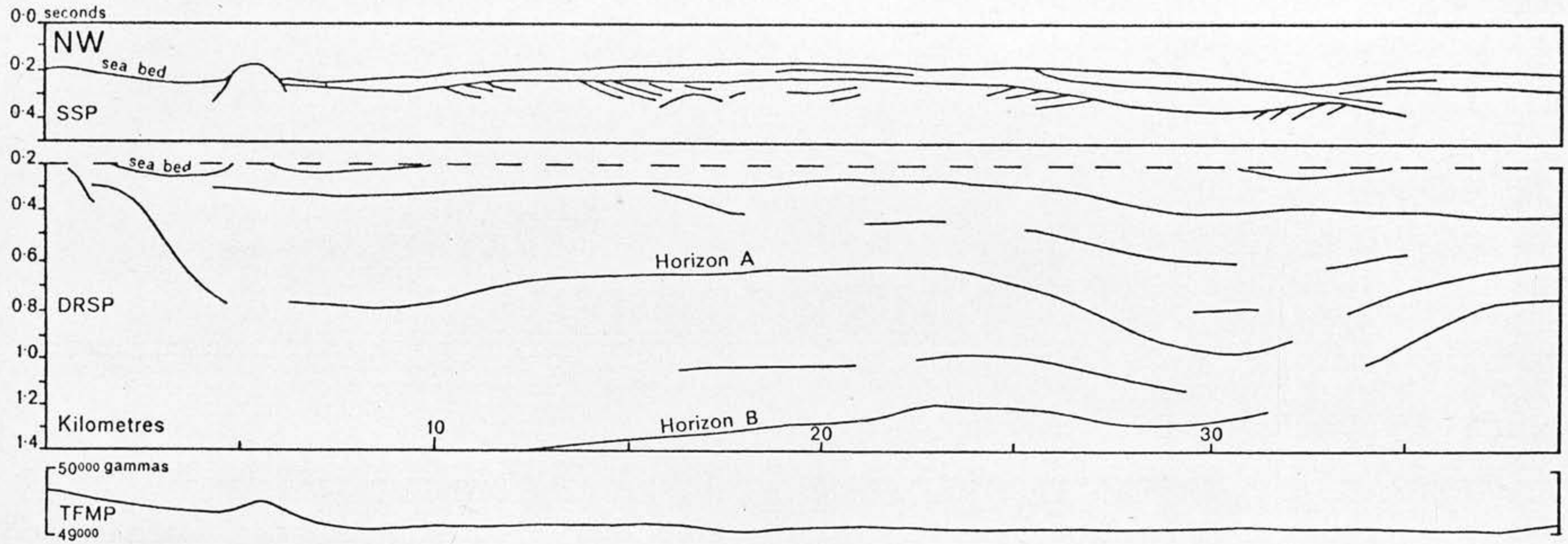



Fig.12a. Section C-C': shallow and deep reflection and shipborne magnetometer profiles. For location see Fig.3. From Binns and others, 1974a.

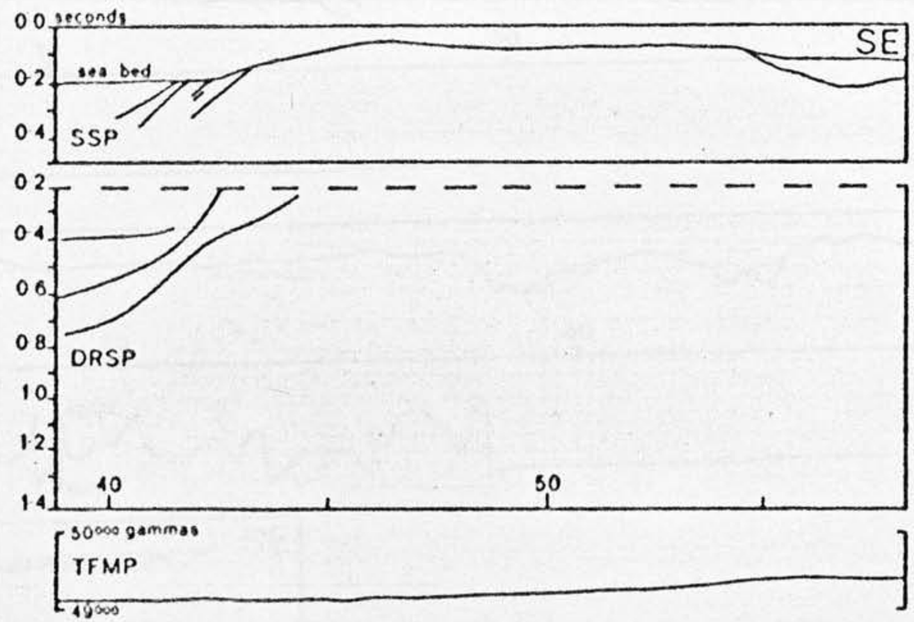



Fig.12b. Section C-C': shallow and deep reflection and shipborne magnetometer profiles. For location see Fig.3. From Binns and others, 1974a.

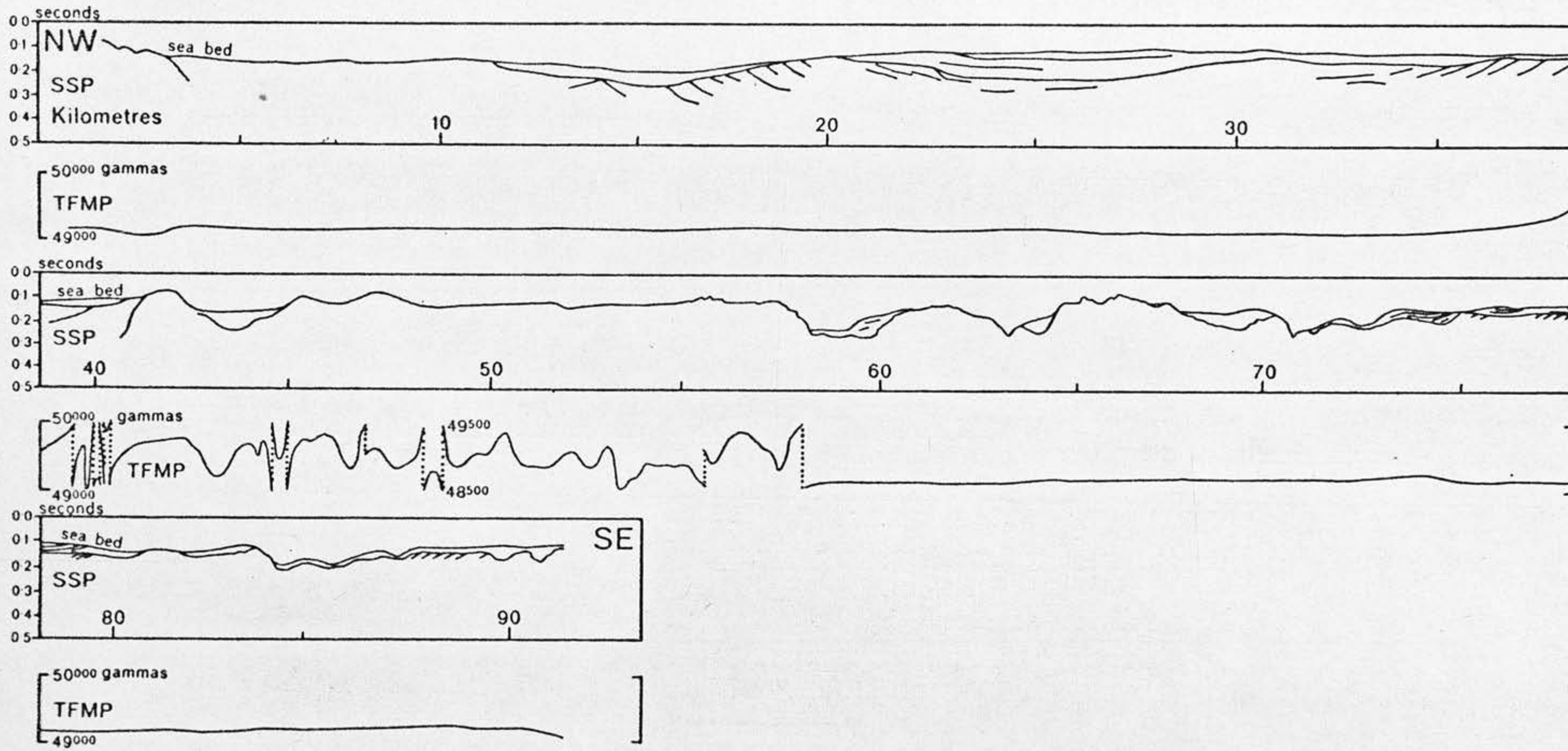



Fig.13. Section D-D': shallow reflection and shipborne magnetometer profiles. For location see Fig.3. From Binns and others, 1974a.

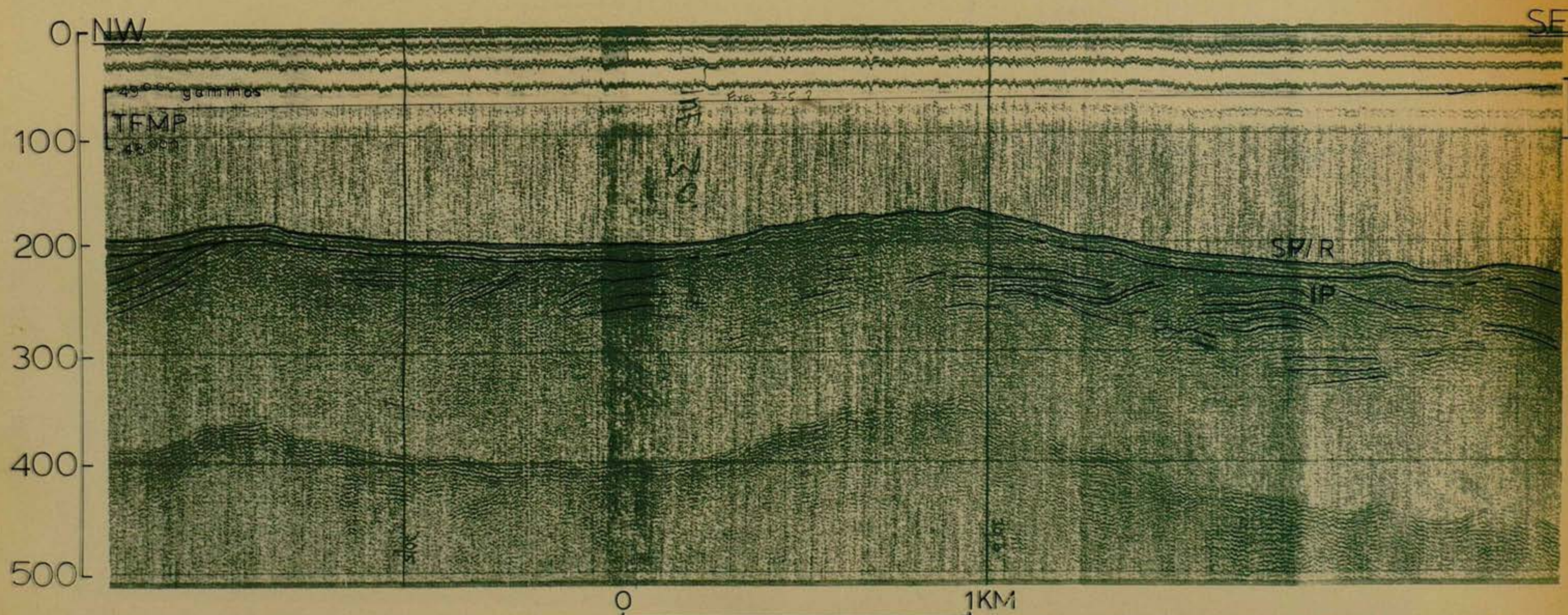



Fig.14. Shallow seismic and magnetometer profiles across a zone of dislocation on the Minch Fault east of Benbecula. SF - Sea-floor; R - Rockhead; IP - Base of initial pulse, vertical scale - two-way time in milliseconds. For location see Fig.5.

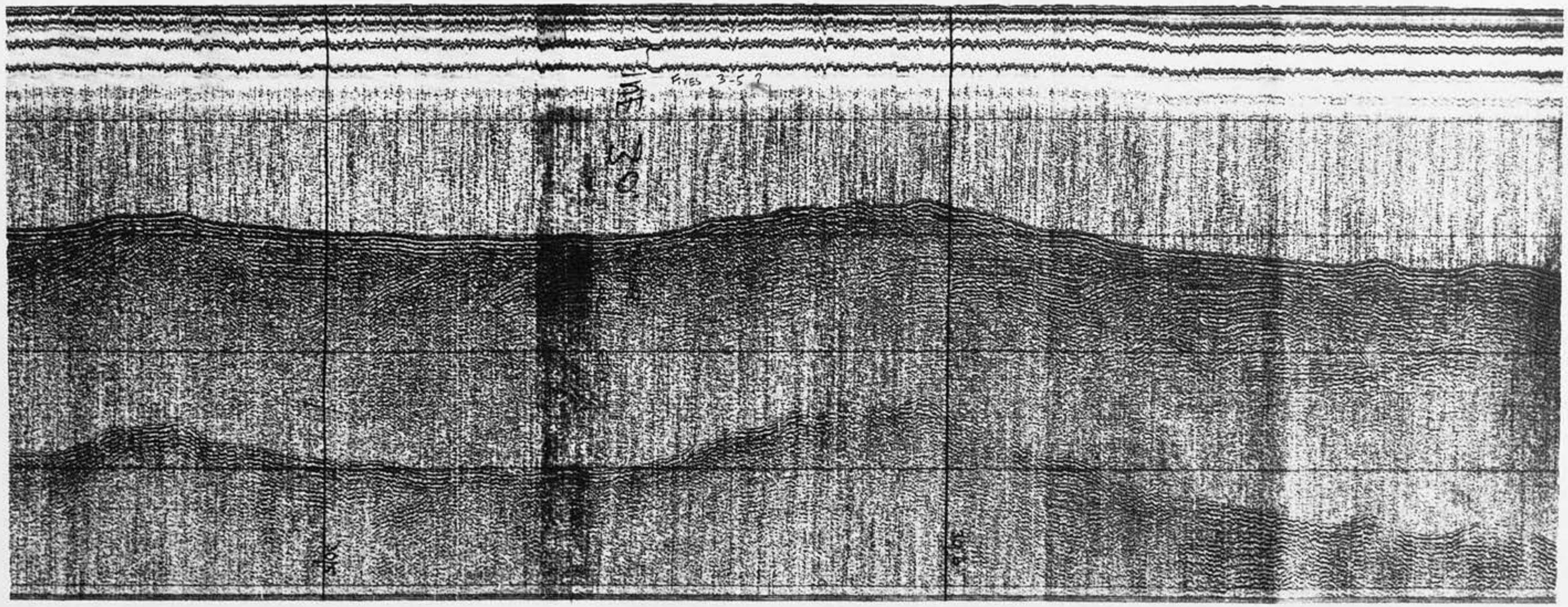


Fig.14. Shallow seismic and magnetometer profiles across a zone of dislocation on the Minch Fault east of Benbecula. SF - Sea-floor; R - Rockhead; IP - Base of initial pulse, vertical scale - two-way time in milliseconds. For location see Fig.5.

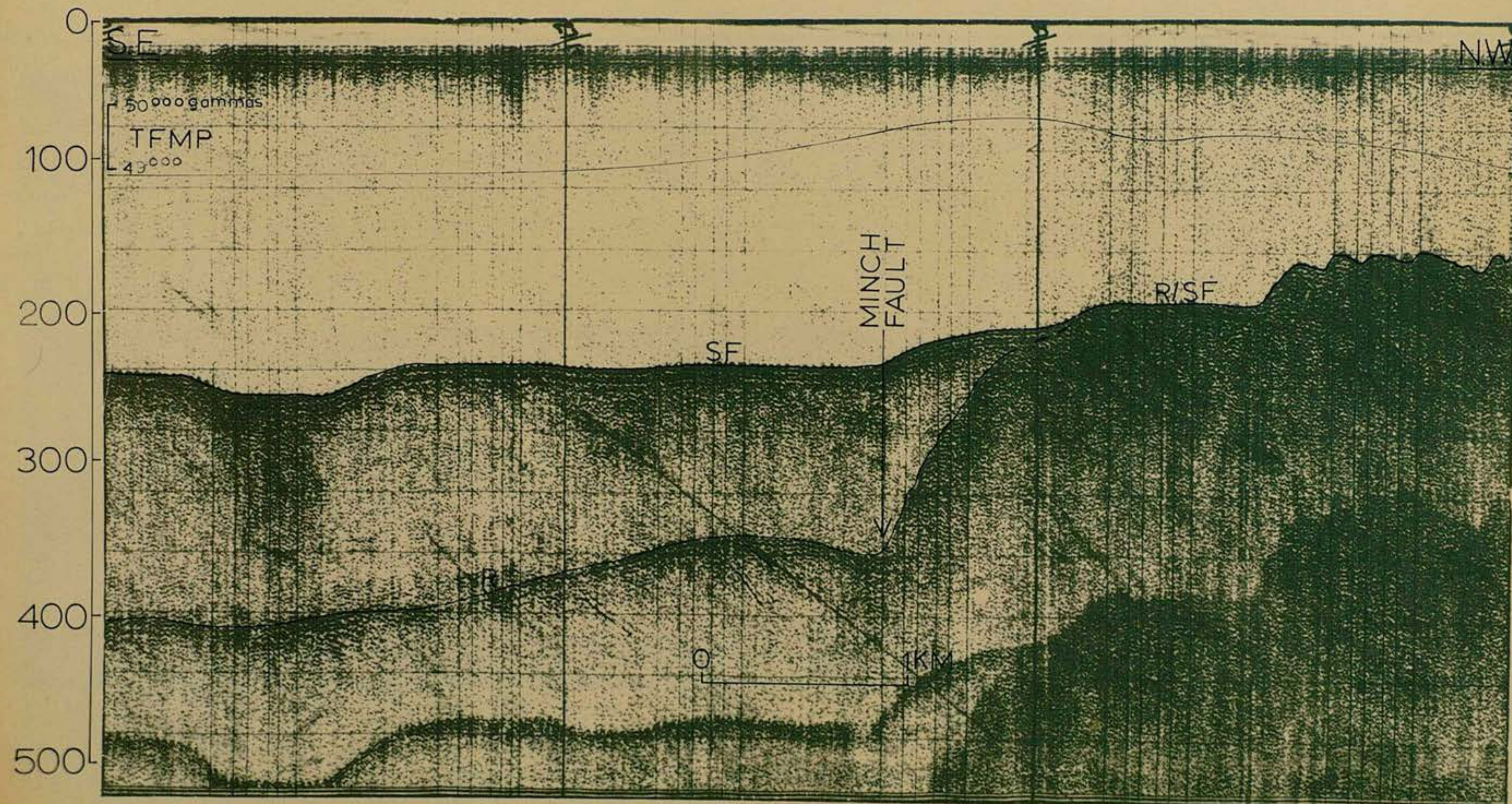



Fig.15. Shallow seismic and shipborne magnetometer profiles across the Minch Fault south-east of Berneray. Note also structureless texture of Quaternary (Formation 2c). For location see Figs. 5 or 26. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds.

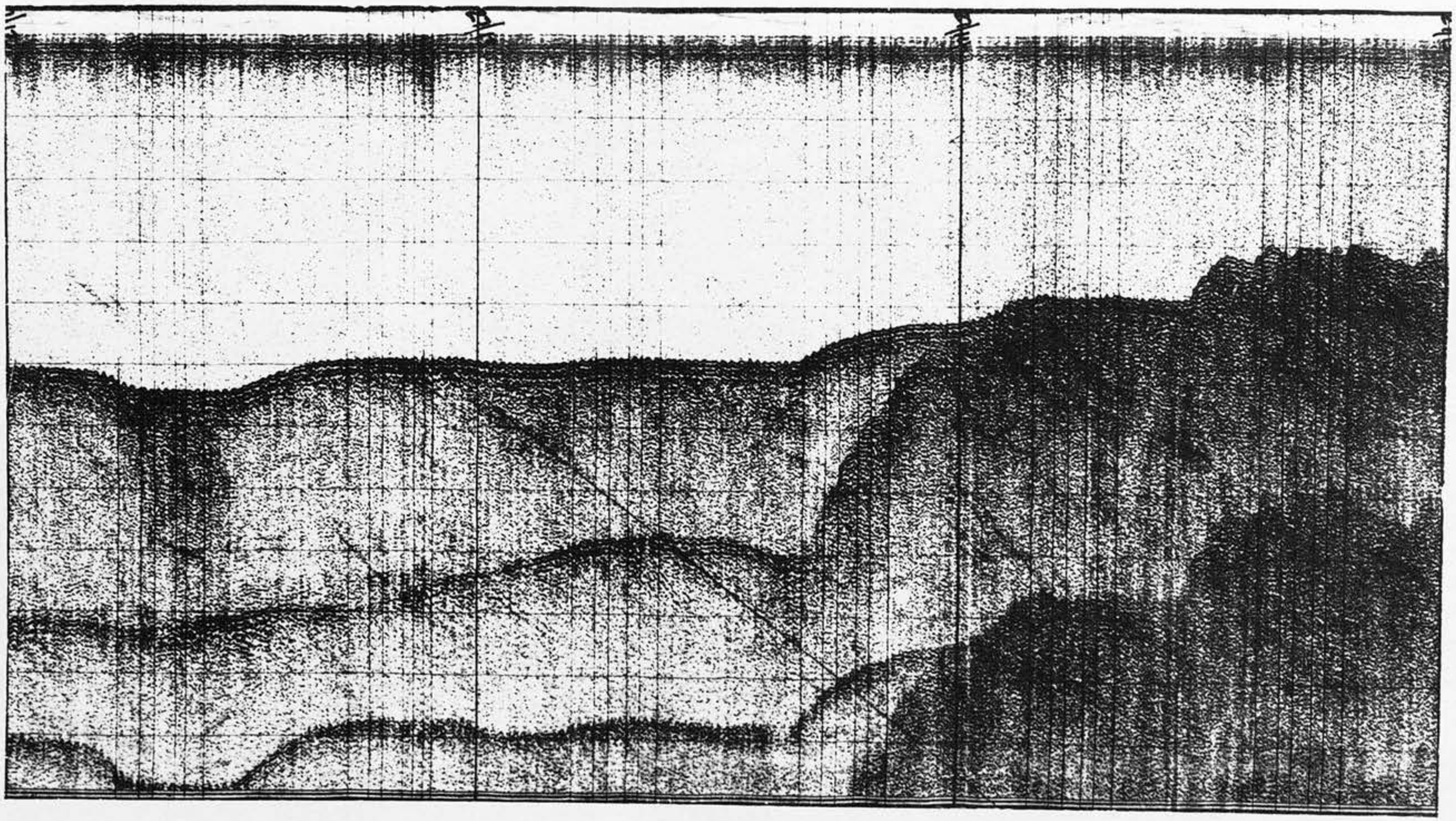


Fig.15. Shallow seismic and shipborne magnetometer profiles across the Minch Fault south-east of Berneray. Note also structureless texture of Quaternary (Formation 2c). For location see Figs. 5 or 26. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds.

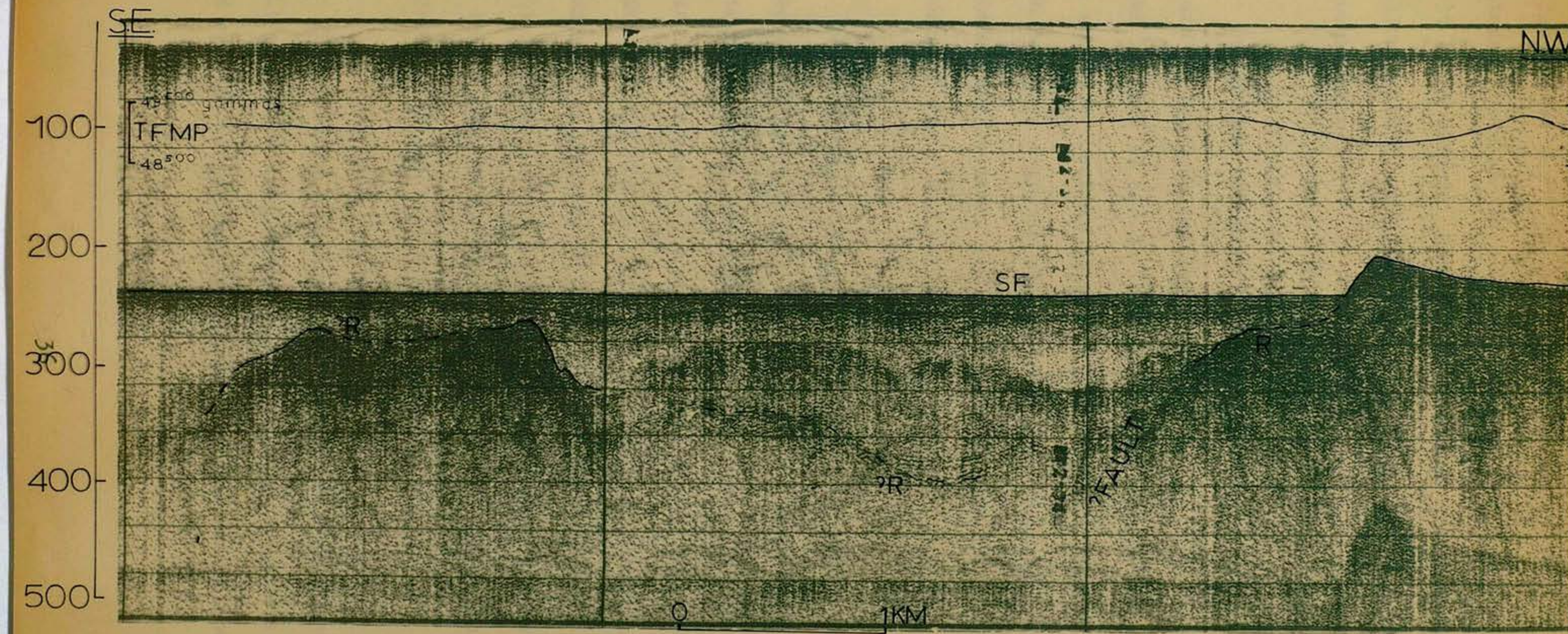



Fig.16. Shallow seismic and magnetometer profiles across a possible location of the Minch Fault north-west of Stanton Banks. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds. For location see Fig.5.

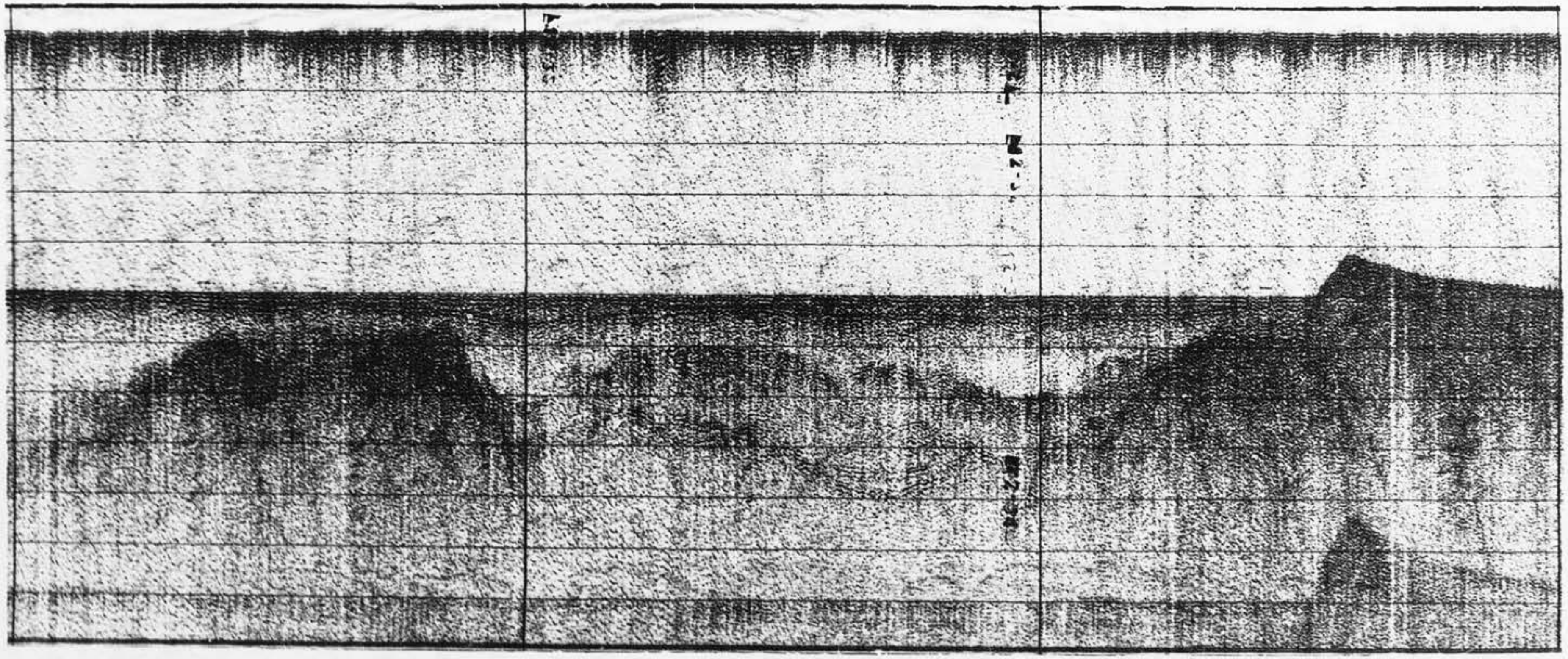


Fig.16. Shallow seismic and magnetometer profiles across a possible location of the Minch Fault north-west of Stanton Banks. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds. For location see Fig.5.

Hebrides and does not occupy the linear channel off Skye (cf Dearnley, 1962). The fault line in this area is based on deep reflection evidence (Seismograph Service Ltd., 1970), geophysical contrasts between the sedimentary rocks on either side of the fault being absent. Zones of dislocation are however evident on shallow seismic profiles (Fig.14) and the fault has been drawn through these.

Southwards the fault branches and can be traced to Barra Island on the deep reflection profiles. Between the sections shown in Figs 11 and 12 the faults pass through the area of the shoals off Pabbay Island (Fig.4). These shoals coincide with negative magnetic anomalies on both airborne and shipborne magnetometer records, and are interpreted as Tertiary lavas (Domain 3b-Fig.9 and Table 1).

South of these shoals contrasts across the fault are strongest (Fig.11 and 15). A steep scarp in rockhead marks the western branch of the fault which here throws bedded Mesozoic sediments (Domain 5a) down to the east against Lewisian gneisses of Domains 28a and 30. The fault line is also indicated by steep gradients on the maps of gravity and magnetic anomalies. A third fault is also seen on deep reflection profiles across the south of the trough but both of the easterly branches have small throws compared with the main westerly branch.

The westerly branch can be traced with confidence southwestwards until the scarp terminates. Beyond this point depressions in rockhead provide morphological evidence for the fault line (Fig.16).

South of $56^0$ 15'N the fault is not detected. It is suggested that the fault southwest of Stanton Banks may downthrow the basement; sedimentary rocks would then lie either side of the fault and geophysical contrasts would be low and difficult to detect at the greater depth of rockhead in the area.

The basement of the Sea of the Hebrides Trough. Knowledge of the basal rocks of the trough is gained from:-

(i) their presence at the edge of the trough where they can be examined in more detail both on and offshore.

(ii) deep reflection profiles (Seismograph Service Ltd., 1970); depths to a basal reflector, Horizon B have been measured on a reconnaisance grid over the trough.

(iii) gravity evidence (R. McQuillin in Binns and others, 1974a, Fig.5).

The geology of Horizon B is discussed in this section and an interpretation is made of domains beneath Horizon B, where these crop out on the rockhead.

Isochrons on Horizon B (Seismograph Service Ltd. 1970) show Horizon B to have the form of a large 'syncline', comprising a line of four depressions trending north-eastwards from Barra Island to north-west Skye. Off Barra Island the Minch Fault truncates the north-western limb of the 'syncline' (Fig.11). Northwards more of this limb remains before truncation by the more northerly trending Minch Fault.

The south-eastern limb of the 'syncline' is best seen off Coll and Tiree. Here Horizon B slopes up to crop out on rockhead (Figs.11, 12 and 17). The outcrop can be seen on shallow reflection profiles and samples of Torridonian sandstone have been taken on Hawes Bank from the rocks beneath it (SH767 and SH768, Fig.9 and Appendix 2).

Northeastwards the strike of this slope parallels magnetic and gravity gradients up to 10km south-west of Rhum. Here the Rhum plutonic centre terminates the gradients but Torridonian outcrops on Rhum and Skye indicate north-eastward continuation of the limb.

At the south-west end of the trough the outcrop of Horizon B (Domains 25 and 27c) takes on a more and more westerly trend, evident on gravity and magnetic maps as well as on seismic profiles. An interpretation of the structure here involves the infilling sediments and is discussed below.

The outcrop of Horizon B on Hawes Bank shows that here it is a Torridonian Sandstone surface. On Rhum (Richey and others, 1961) and Skye (Peach and others, 1910) Permo-triassic rocks lie unconformably on the Torridonian. Geophysical evidence (Domain 25, Table 1) indicates that Torridonian (possibly of a more pelitic facies) or Palaeozoic rocks underly the Permo-triassic off Tiree, and it is therefore inferred that a sub-Permo- triassic unconformity crops out on rockhead along the eastern margin.

There is no evidence however that Horizon B coincides with this unconformity in the centre of the trough. Although reflections below Horizon B are consistent with reflections from within the Torridonian

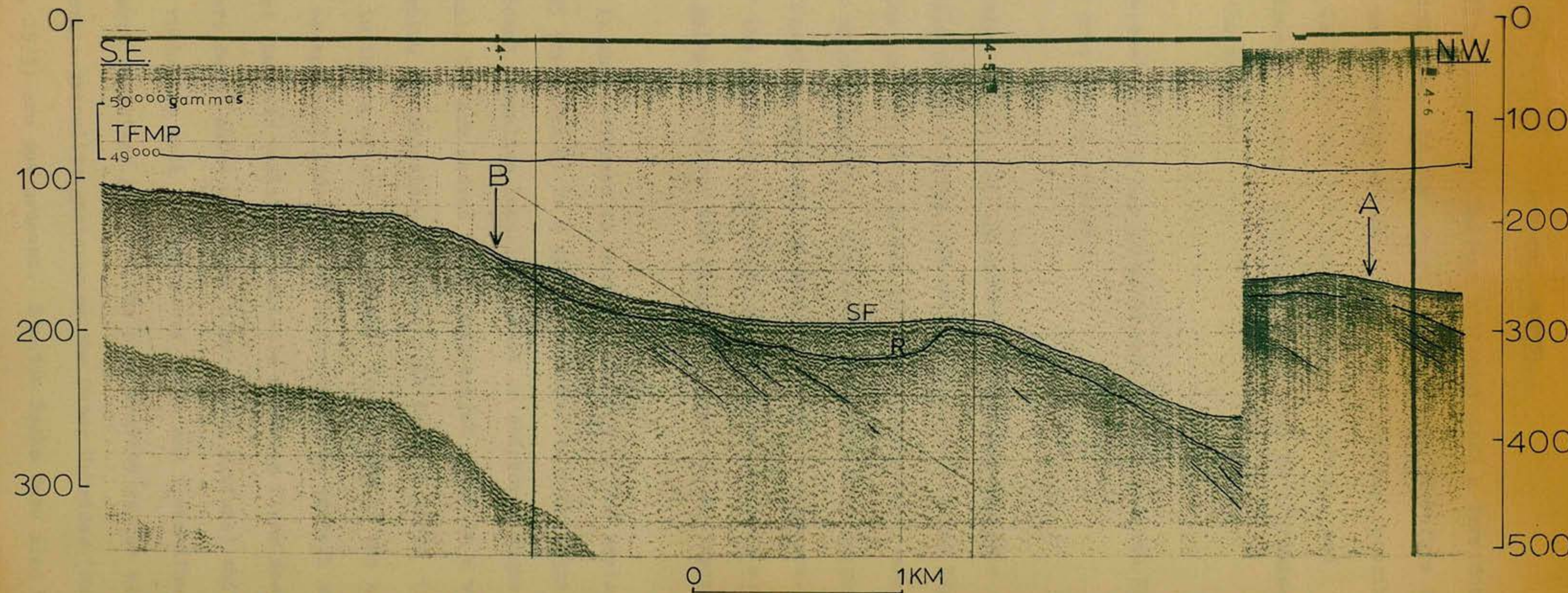



Fig.17. Shallow seismic and shipborne magnetometer profiles across the outcrops of Horizons A and B on rockhead N.W. of Tiree. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds. For location see Fig.5.

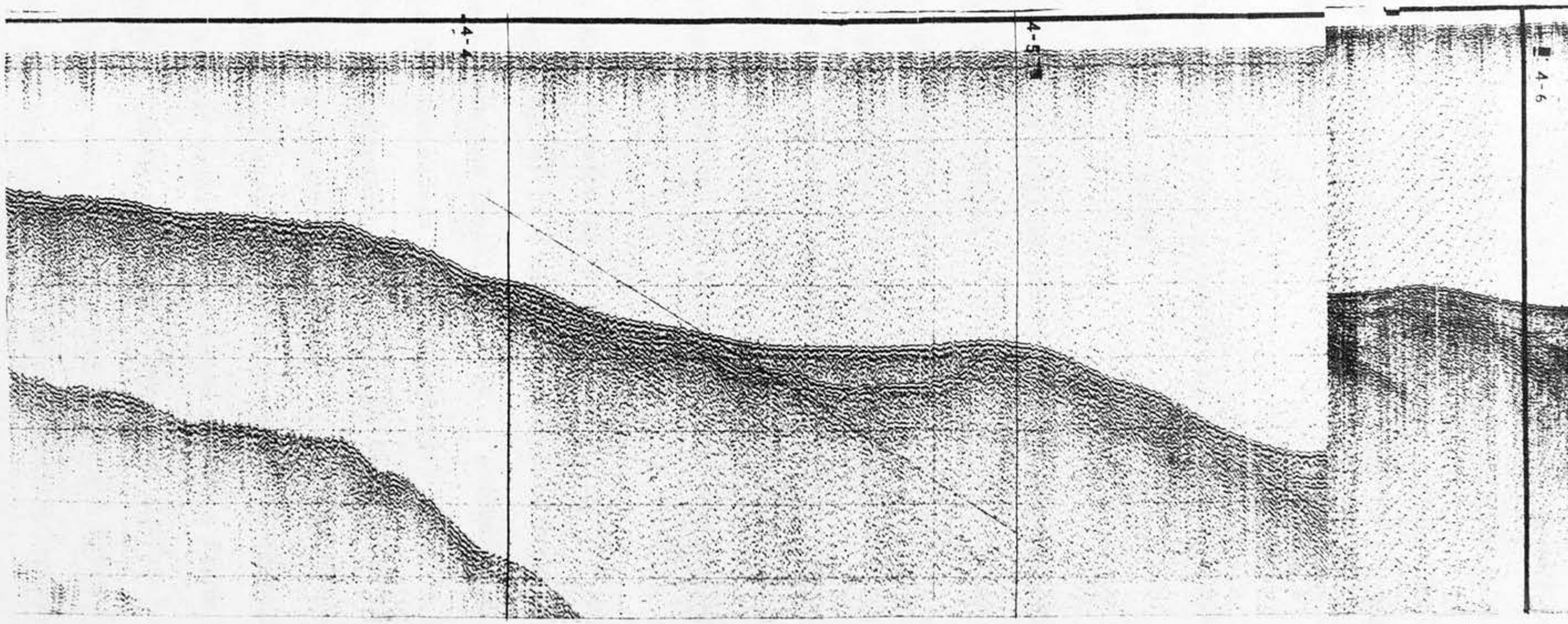



Fig.17. Shallow seismic and shipborne magnetometer profiles across the outcrops of Horizons A and B on rockhead N.W. of Tiree. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds. For location see Fig.5.

the possibility exists that Horizon B transgresses a Torridonian-Palaeozoic boundary. In the centre of the trough therefore it could be an unconformity between a Palaeozoic surface, possibly as young as Carboniferous (cf Vischer, 1943, Plate 6), and younger sedimentary rocks. Alternatively it may be a prominent bed within the sequence.

An interpretation is now given of the domains beneath Horizon B, where these crop out on rockhead.

A Lewisian domain (31a) is defined on the aeromagnetic map by an area of a high positive anomalies which includes Coll and Tiree. The nature of the boundary with Domain 15 is uncertain being seen only on one shallow seismic profile. Similarly the fault running north-west from Gunna Sound is based on the same aeromagnetic evidence. The boundary of the Lewisian north-west of Tiree, however, is clear on shallow seismic profiles and shipborne magnetometer traces (Fig.11).

There is some evidence as to the lithology of the Lewisian offshore. Sample SH725 (Appendix 2) is a diopside-scapolite rock suggesting that the exceptional anomalies locally present on shipborne magnetometer traces (Domain 32) are caused by magnetite-rich bands in a variable gneiss of which the diopside-scapolite rock forms a part. (Geological Survey 1 - in Sheets 42 and 50, Tiree). Comparison of the areas giving the exceptional anomalies with the rockhead isobath map suggest that the less resistant, variable gneisses floor deeper areas of Skerryvore Bank (which also have a more even surface) whilst uneven shoals and rocks (as well as Skerryvore Islet and Tiree itself) are formed of more resistant gneiss. The high gravity values associated with pyroxene - granulite gneisses on the Outer Hebrides (McQuillin and Watson, 1973) are not present. Stanton Banks have also been interpreted as Lewisian outcrop (Domains 28b and 31b, Table 1).

Both Domains 27a and 27b have been calibrated as Torridonian Sandstone. Domain 27c is a topographically lower domain than either 28b and 31b and has been interpreted as Torridonian on shipborne magnetic evidence. An alternative interpretation (D. K. Smythe, personal communication) is that it is Lewisian, shipborne magnetic anomalies being damped by the greater depth to rockhead. If this interpretation is correct then locally strong reflections at depth (e.g. Fig.16) are from moraine and not rockhead.

Domain 25, which differs from Domain 27 in having a more even surface is tentatively assigned a Torridonian (possibly a more pelitic facies than Domain 27) to Palaeozoic age. It fringes the Lewisian off Tiree southwards but is conjectured to have been faulted out between two profiles.

A similar age has been assigned to Domain 18, which fringes the south of Stanton Banks, Fig.18. The boundary with the Lewisian is not obviously faulted on shallow seismic profiles. When interpolated between profiles on bathymetric evidence it is not rectilinear and is therefore inferred not to be a fault.

<u>The geology of the infilling sediments of the Sea of the Hebrides Trough</u>. The sedimentary rocks lying above Horizon B and cropping out as Domains 5a and 12b have been interpreted as Permian to Cretaceous sediments (Table 1). Between Tiree and the southern islands of the Outer Hebrides the infilling sediments have a

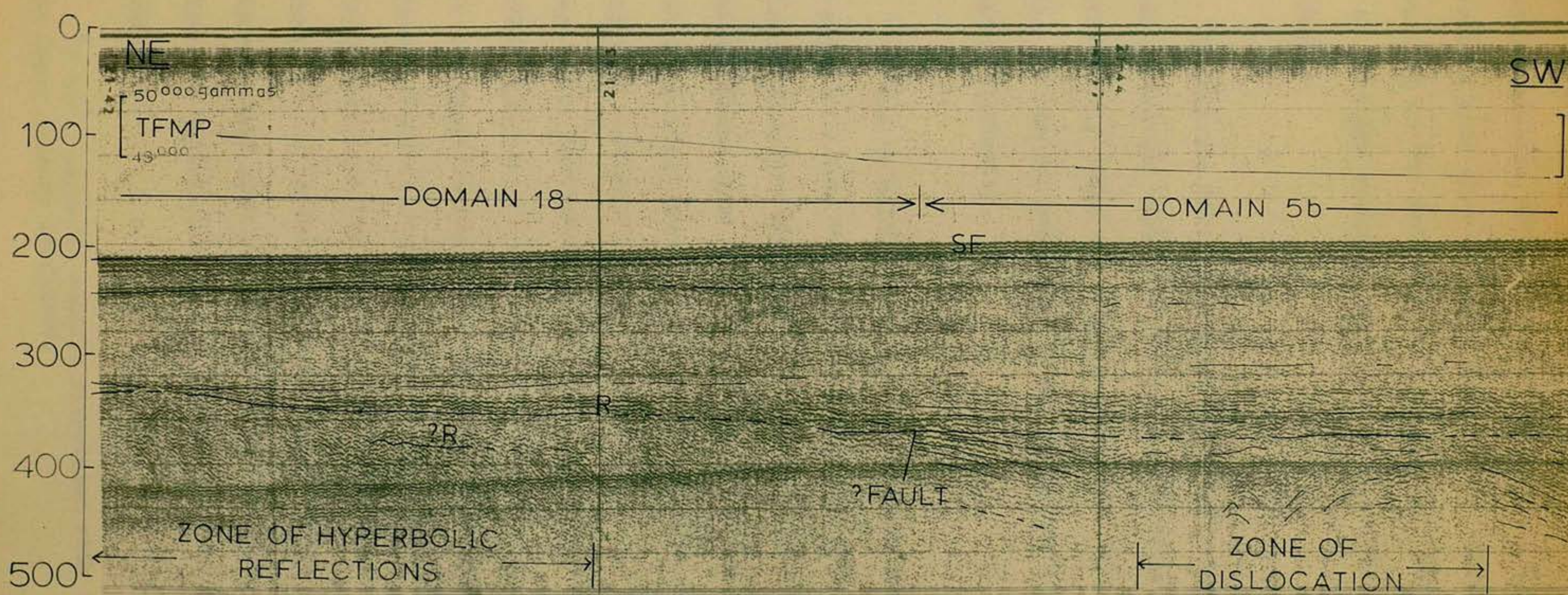



Fig.18. Shallow seismic and shipborne magnetometer profiles across Domains 5b/18 south-west of Stanton Banks. Quaternary (Formation 2c) sediments lie on rockhead which is not well defined here: the top of the zone of hyperbolic reflections may be rockhead in the north-east. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds. For location see Figs. 5 or 26.

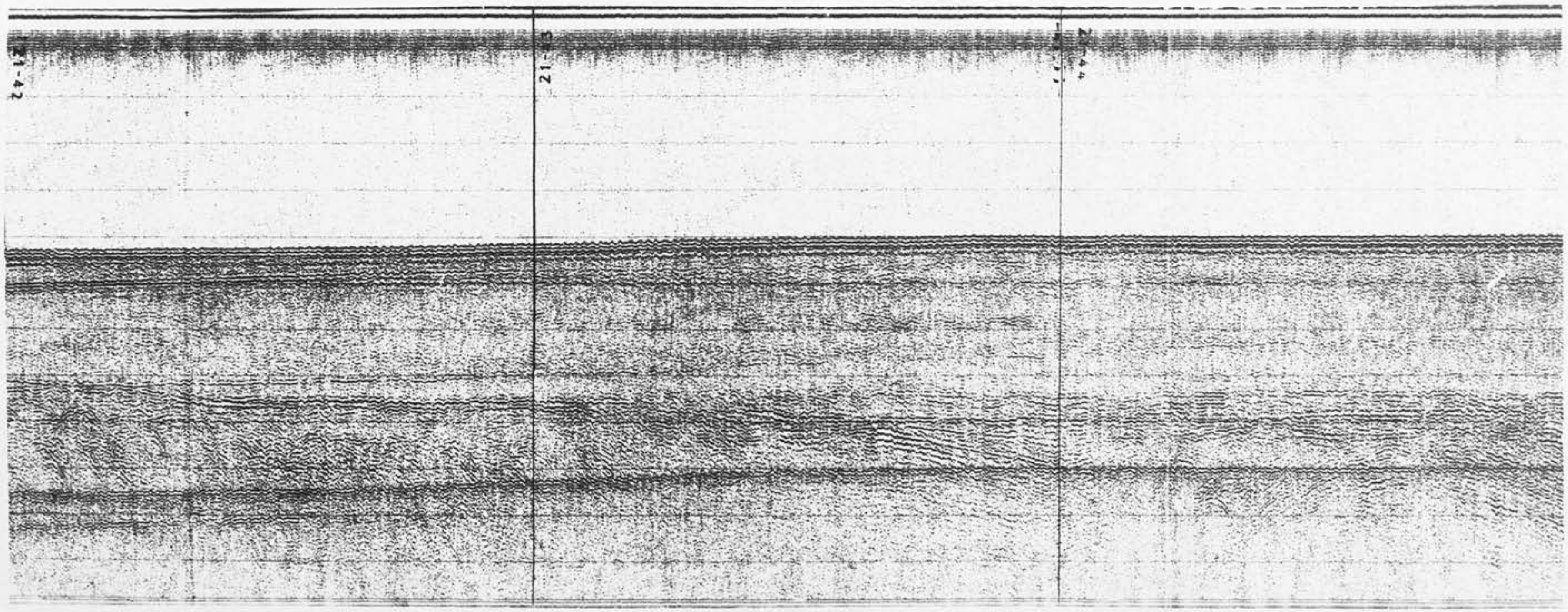



Fig.18. Shallow seismic and shipborne magnetometer profiles across Domains 5b/18 south-west of Stanton Banks. Quaternary (Formation 2c) sediments lie on rockhead which is not well defined here: the top of the zone of hyperbolic reflections may be rockhead in the north-east. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds. For location see Figs. 5 or 26.

regional dip north westwards in towards the Minch Fault. The two Mesozoic samples, SH133 and SH177 (Fig.9 and Appendix 2) must therefore come from the upper part of the sequence: in addition lavas lie on the sediments (Fig.21a). This indicates that little or no Tertiary sediment lies below rockhead in this part of the trough.

Within the infilling sediments a reflector, Horizon 'A', has been picked and contoured (Seismograph Service Ltd., 1970). This horizon only crops out with certainty off Coll and Tiree (Figs.5 and 17). It has not been sampled and any attempt to estimate its age must be tentative.

It can be best related to sampled rock off Benbecula. It is not present on a deep reflection profile over Domain 12a (west of the Minch Fault) and this suggests Horizon A is younger. Comparison of the thickness from 'B' to 'A' east of the fault with the thickness 'B' to rockhead west of the fault (Seismograph Service Ltd., 1970) suggests that west of the fault 'A' is at a stratigraphic level just above that of rockhead. This has been confirmed (SH206 and SH207, Appendix 2) as Permo-triassic to Lower Jurassic in age. It is suggested therefore that both off Benbecula and off Coll and Tiree, where it forms a prominent scarp on the sea-floor, it is a reflection from the top of the Permo-triassic or within the Lower Jurassic* (cf Smythe and others, 1972). This interpretation is not inconsistent with the structural relationship of 'A' to the Middle Jurassic sediments of Neist Point, Skye (Geological Survey, 1 in sheet 80).

*A small magnetic anomaly associated with it may be caused by an Upper Liassic Ironstone.

Times to Horizon A and between A and B have been measured by Seismograph Service Ltd., (1970). South of the latitude of Eriskay the form of 'A' broadly reflects that of 'B'. A major divergence occurs off north-west Skye where a depression in B coincides with an anticline in A. The sediments between A and B in this area have been interpreted by Smythe and others (1972), on the basis of seismic velocity, as Permo-triassic sandstones.

According to Seismograph Service Ltd., (1970) 'A' also crops out on the shoal at 56° 40'N, 07° 18'W (Domain 12c, Fig.9). The surface of this shoal and the associated magnetic anomalies indicate it is formed of Domain 12 rocks intruded by basic igneous rock. However, outcrop of 'A' at this point, together with the regional north-westerly dip, requires a fault to account for the repeat of A down dip. Although there is a prominent scarp at the south-east of the shoal (Fig.4) no fault is seen on the deep reflection profiles to the south and north of the shoal. A fault shown by Seismograph Service Ltd. (1970) as bounding the south-west of the shoal has been questioned (D. K. Smythe, personal communication) as there is no supporting gravity evidence. The evidence is therefore contradictory and no clear interpretation can be made.

Tertiary lavas of the Canna Ridge cover the sediments at the north-east of the trough (indicated by a gravity low). Domain 10, to the east of this however is interpreted as Mesozoic sediments.

<u>Palaeozoic and Mesozoic sediments outside the Sea of the Hebrides Trough</u>. Four domains, 5b (Fig.18), 5e, 12d and 15 have been interpreted

as outliers of sediment faulted into older rocks. Little evidence is available about Domain 15 which has therefore been assigned a wide age range (late Palaeozoic to Cretaceous).

Domain 5e (Fig.19b) has typical Mesozoic bedding and both deep and shallow reflection evidence indicate it is an asymmetric trough faulted at the north-west and containing bedded Mesozoic sediment lying unconformably on older rocks to the south-east. The nature of the south-west and north-east boundaries are uncertain but the aeromagnetic map suggests that an extension of the fault running through Gunna Sound may form the south-west margin. I have interpreted the north-east margin (with Domain 25) as a fault.

Domain 12d is characterised by an extremely smooth surface, mostly structureless, but locally with poorly-developed bedding. Its separation from the 'trough' Domain 12b is discussed below (p 47). It is bounded to the south-west by the Camasunary-Skerryvore Fault. A boundary of uncertain nature separates it from Domain 18 and the rectilinear nature of its boundary with Domain 31b is taken as evidence of a fault.

South-western termination of the trough. Southwards to Tiree the narrowing of the trough in part reflects the converging trends of the Minch and Camasunary-Skerryvore faults but this does not explain the wedging out of Domain 5a (Fig.9).

The shallow and deep seismic evidence is presented in Figs.5, 19a and 20. Two features must be explained; firstly the narrowing of Domain 5a southwards from Skye and secondly the termination of

Domain 5a in the south by the south-westerly trending outcrops of Domains 12b and 27c. Both these features are reflected on the gravity and aeromagnetic maps. In an attempt to elucidate the structure, domain boundaries are considered first and then the structural evidence from the deep and shallow seismic profiles:-

(i) North-west boundary of Domain 27c. - Infilling sediments crop out on rockhead in Domain 5a and the steep scarp separating domains 5a and 27c is interpreted as the southerly continuation of a branch of the Minch Fault.

(ii) North-east boundary of Domain 27c. - This fault is based on limited shallow seismic evidence with supporting aeromagnetic evidence in the form of a gradient defined by the + 100 to + 300 gamma contours.

(iii) South-east boundary of Domain 27c. - This boundary is considered in two parts. The southern section is interpreted as an extension of the fault east of Stanton Banks. The presence of a zone of disturbance on a shallow seismic profile and the rectilinear nature of this section of the boundary is taken as evidence that it is a fault, not an unconformity. The northern section of the boundary does not coincide with an extension of this fault and no fault is seen on a deep reflection profile (Seismograph Service Ltd., 1970) crossing it. It is therefore interpreted as an unconformity.

(iv) North-west boundary of Domain 12b. - This is defined by the outcrop of Horizon A and can be traced south-westward and then westwards up to a fault.

(v) North-west boundary of Domain 25. - This is defined as the outcrop of Horizon B and can be traced southwestwards and then southwards.

(vi) North-east boundary of Domain 12d. - This is the conjectured continuation of the fault at the northeast of Domain 27C.

The structural evidence is summarised in Fig.20 and does not allow a unique solution. The thickness of Domain 12b sediments and geometry of Horizon B prior to the structural events under consideration are continuous variables about which we have no information: the presence or absence of faulting is a discontinuous variable about which we have limited information: north-easterly tilting of the Sea of the Hebrides Trough is a third possible variable which must be considered.

The narrowing southwards to Lat. 56°40'N can be accounted for by the acute angle at which the Minch Fault intersects the major synclinal structure of the trough: a north-easterly tilting of the trough or north-westerly cross-faulting could also accentuate it. The narrowing of Domain 12b outcrop north-eastwards is consistent with the tilting to the north-east of a previously north- westerly dipping succession followed by erosion to the horizontal.

Southwards from Lat. 56°40'N Horizon B appears to be raised and repeated by the faults surrounding Domain 27C and these together with a combination of the present rockhead topography and the topography of Horizon B may be responsible for the outcrop pattern.

If this is so it follows that the rocks exposed on rockhead in the Stanton Banks - Skerryvore areas are representative of lower levels in the trough. The fault south-west of Stanton Banks (Fig.18) terminates this structural high and throws down the Mesozoic sediments of Domain 5b.

Tertiary geology. Tertiary igneous activity is of major importance. Two Tertiary plutonic centres, the Black Cuillins and Rhum, both crop out close to the Camasunary-Skerryvore Fault. Extension of the Rhum centre off south-west Rhum is indicated by magnetic and morphological evidence (Domains 1 and 2, Table 1). This offshore extension has been terminated by a north-westerly fault based on rectilinear morphological and magnetic gradients.

Domain 3a is interpreted as an extension of the north Skye basalt flows south-westwards forming the topographic plateau of the Canna Ridge. The thinness of these lavas is indicated by the low gravity values. Close to the Minch Fault zone, these are a number of shoals within the area of Mesozoic sediment. Their geophysical character is similar to that of the Canna Ridge and the shoals are interpreted as outliers of Tertiary basalt lavas (Fig.21a). A similar shoal is present at $56^{0}47$'N/07 10'W (Fig.31).

Off South Uist shoal areas with the magnetic character of basic igneous rocks occur along the line of the Minch Fault. The "basalt scarps" seen on the shoals off Pabbay Island are absent here.

Off Neist Point, north-west Skye dolerite sills are detected on shallow seismic and magnetic records and crop out as a series of shoal areas. The concordant, intrusive nature of these rocks is clear

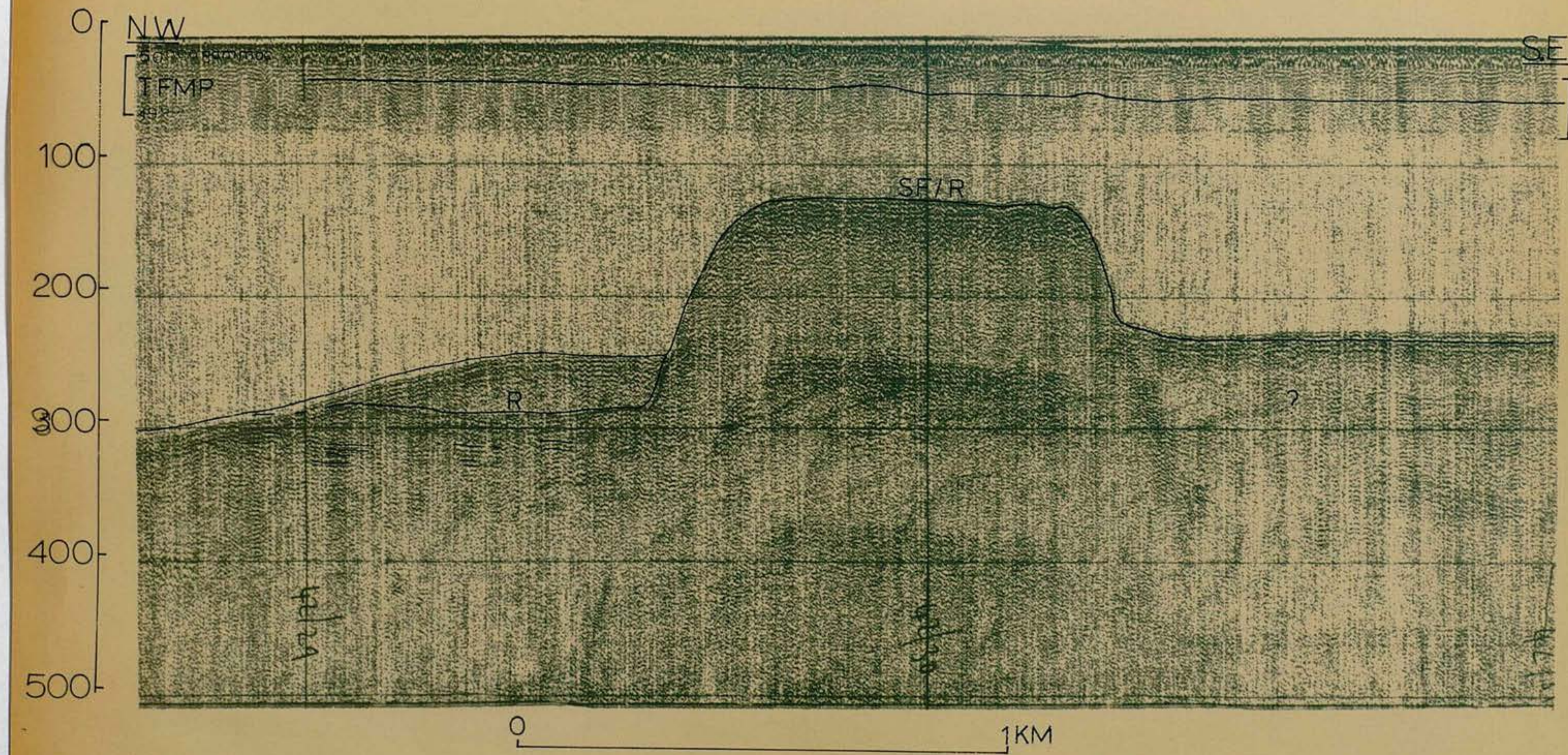



Fig.21a. Shallow seismic and shipborne magnetometer profiles across a shoal of Tertiary basaltic lava, south-west of Pabbay Island, Outer Hebrides. SF - Sea-floor; R - Rockhead; Vertical scale-two-way time in milliseconds.

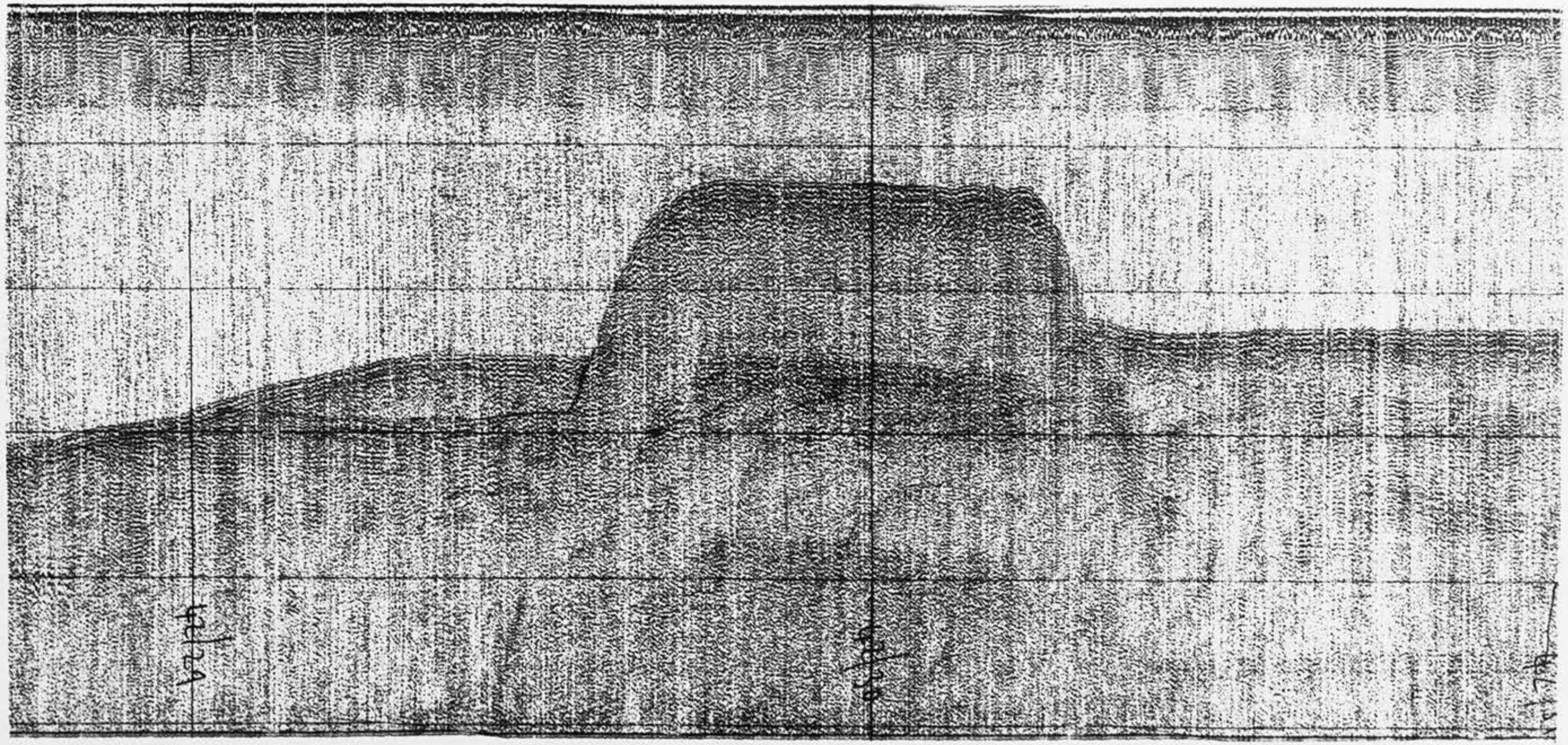


Fig.21a. Shallow seismic and shipborne magnetometer profiles across a shoal of Tertiary basaltic lava, south-west of Pabbay Island, Outer Hebrides. SF - Sea-floor; R - Rockhead; Vertical scale-two-way time in milliseconds.

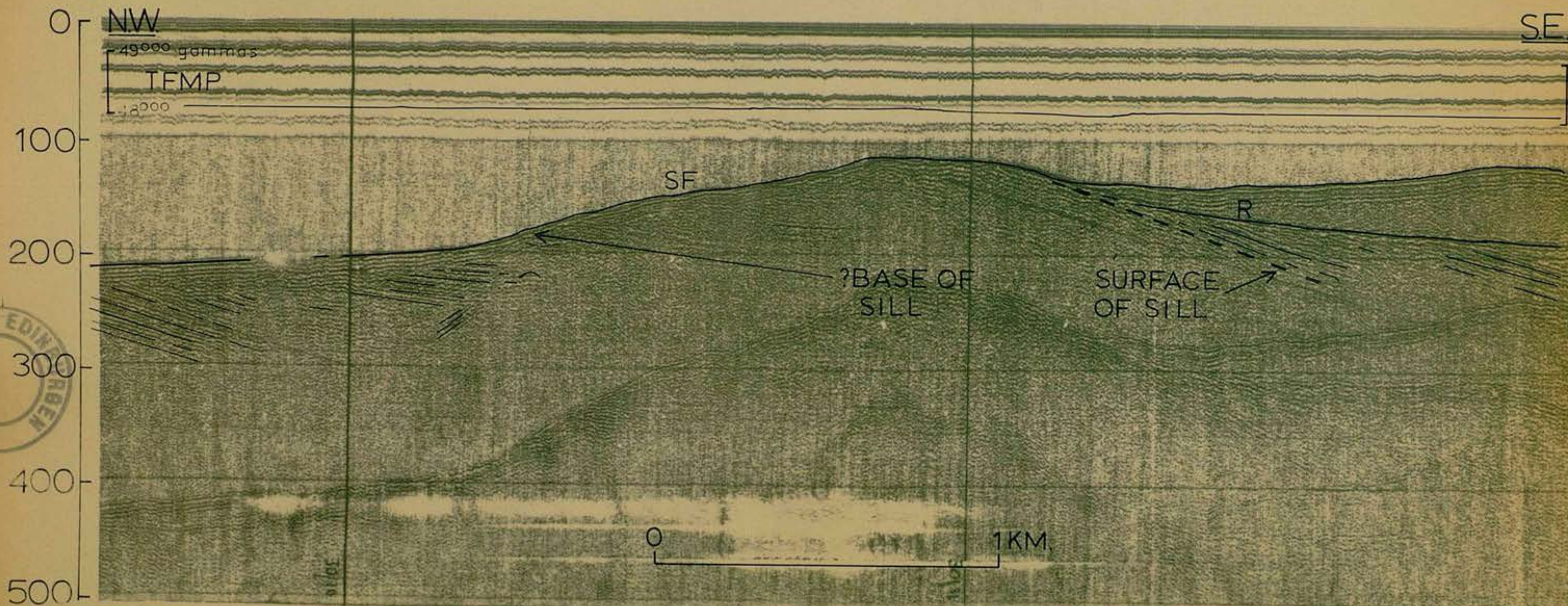



Fig.21(b). Shallow seismic and shipborne magnetometer profiles across a sill intruded into Jurassic sediments, west of Neist Point, Skye. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds. For location see Fig.5.

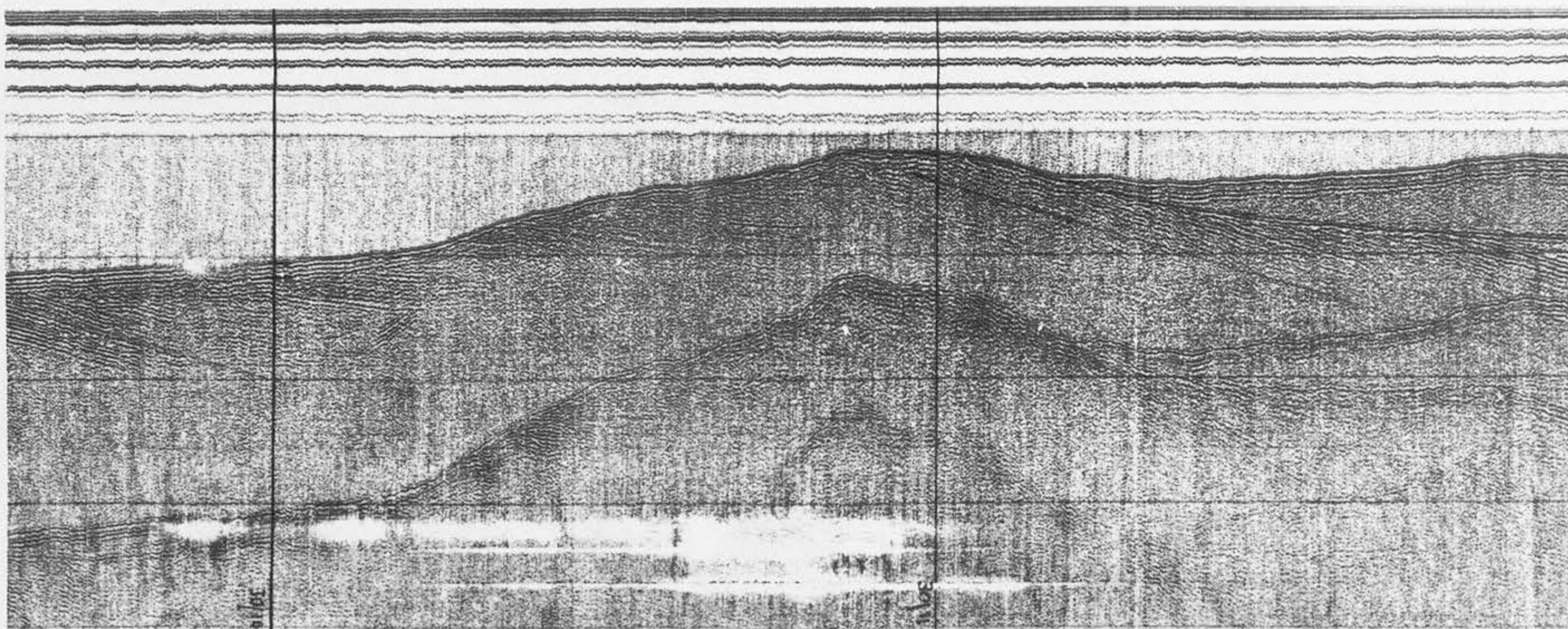


Fig.21(b). Shallow seismic and shipborne magnetometer profiles across a sill intruded into Jurassic sediments, west of Neist Point, Skye. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds. For location see Fig.5.

on the profiles (Fig.21b) which are interpreted as the offshore continuation of the succession of Jurassic sediments and Tertiary sills seen on Neist Point (Geological Survey lin. Sheet 80).

The faulting which in part may be responsible for the repetition of Horizon B across the southern end of the trough has been described above. By analogy with faulting on land, for example with the Loch Assapol Fault on Mull, and the faults cutting Tertiary lavas on Skye, this may be of Tertiary age.

An east-west trend, which may be fault-controlled is defined by the rectilinear northern margin of Hawes Bank and the northern scarp of the Tertiary lava shoal at 56°47'N/07°10'W (Figs. 3 and 4). The truncated northern margin of the Tertiary lava shoal suggests a post-lava age.

A scarp in rockhead between Rhum and Skye and the obvious lowering of the lava base from Rhum to Canna are together taken as evidence for the fault between the latter islands. This interpretation is consistent with the morphological evidence of Mesozoic rock in Domain 10.

2.2.4. Camasunary-Skerryvore Fault to the Great Glen Fault.

The line of the Camasunary-Skerryvore Fault. The Camasunary Fault can be traced southwards from Skye where Mesozoic sediments are thrown down to the east against the Torridonian (Peach and others, 1910). On the profile on Fig.13 the fault is inferred to lie in a hollow between Domains 6 and 27a. South of Rhum the fault is again visible on a seismic profile (Fig.22). Southwards again the cover of lavas prevent detection by seismic profiling and interference from the Ardnamurchan plutonic centre obscures the gravity evidence. A boundary, taken to be the fault, is evident on shipborne magnetic profiles.

East of Coll, a steep gravity gradient indicates the presence of a fault close to the coast, probably following the linear bathymetric trench. It is here interpreted as the southwards extension of the Camasunary Fault on the basis of its structural similarity, and is referred to as the "Camasunary-Skerryvore Fault". It is assumed to throw Mesozoic rocks, covered by lavas, down to the east against the Lewisian of Coll and Tiree. A horizontal displacement as the Camasunary-Skerryvore Fault is cut by the fault through Gunna Sound is based on aeromagnetic evidence.

Off the Skerryvore Bank the fault is clearly seen on shallow and deep seismic profiles (Fig.23) and on the gravity map. It forms a prominent Lewisian scarp similar to the Minch Fault scarp south of the Outer Hebrides. Off south-east Tiree a small horizontal displacement is based on aeromagnetic evidence.

Geophysical contrasts across the fault as it divides the Lewisian of Skerryvore Bank from the triangular block of Lewisian within the trough are not strong but the fault is seen on a deep reflection profile (Fig.10).

East and south-east of Stanton Banks bedded sediments are

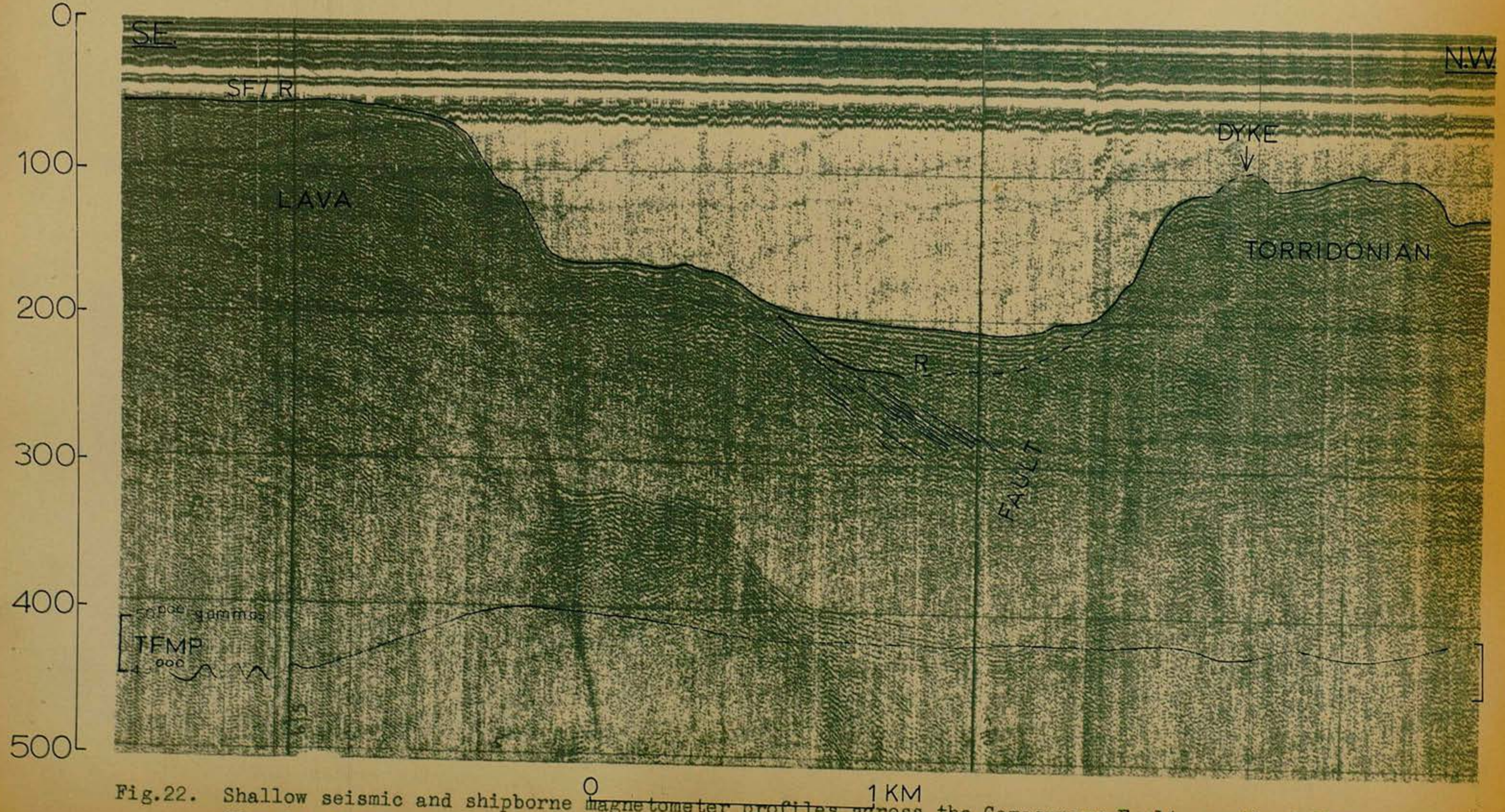


Fig.22. Shallow seismic and shipborne magnetometer profiles across the Camasunary Fault, south of Rhum. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds. For location see Fig.5.

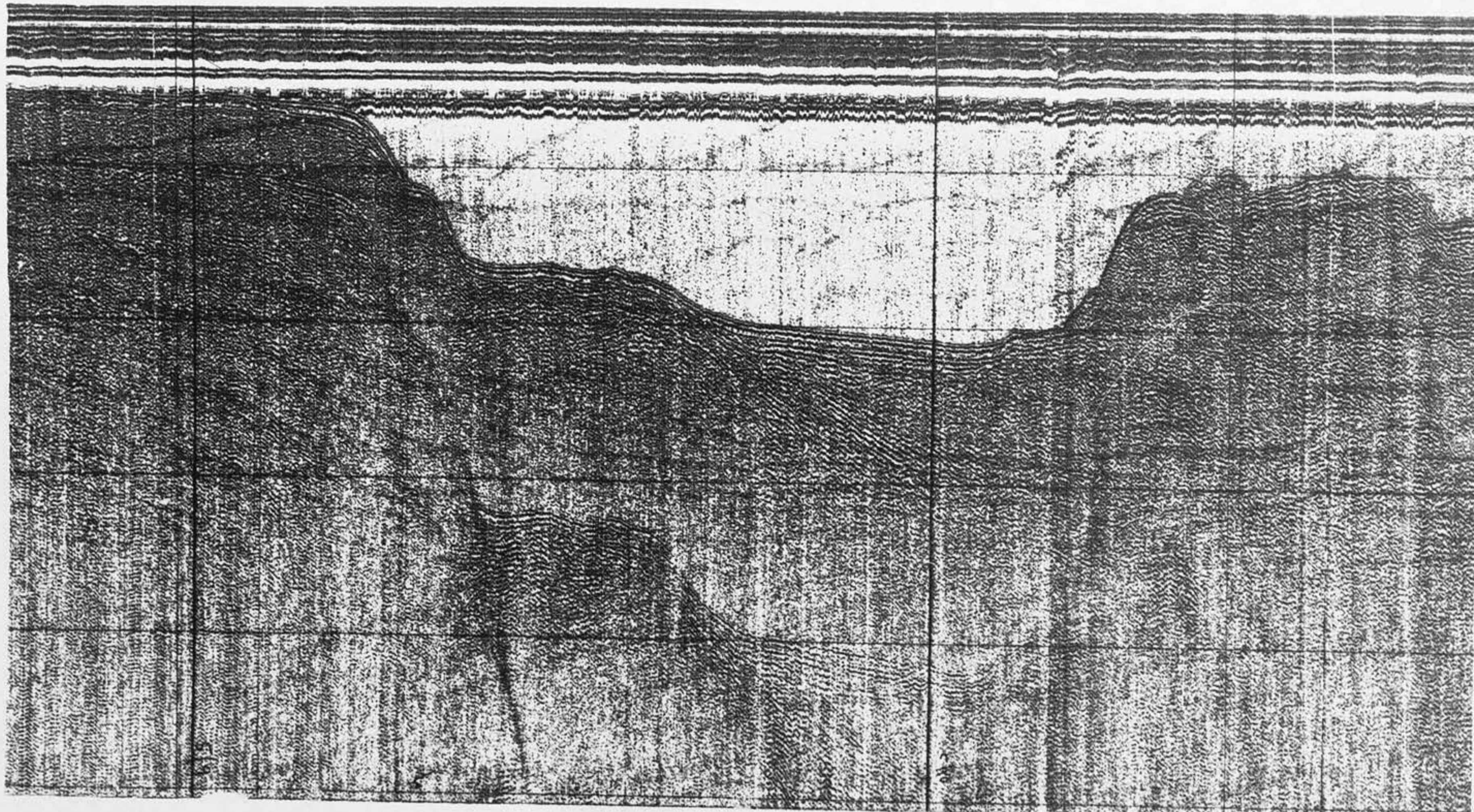


Fig.22. Shallow seismic and shipborne magnetometer profiles across the Camasunary Fault, south of Rhum. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds. For location see Fig.5.

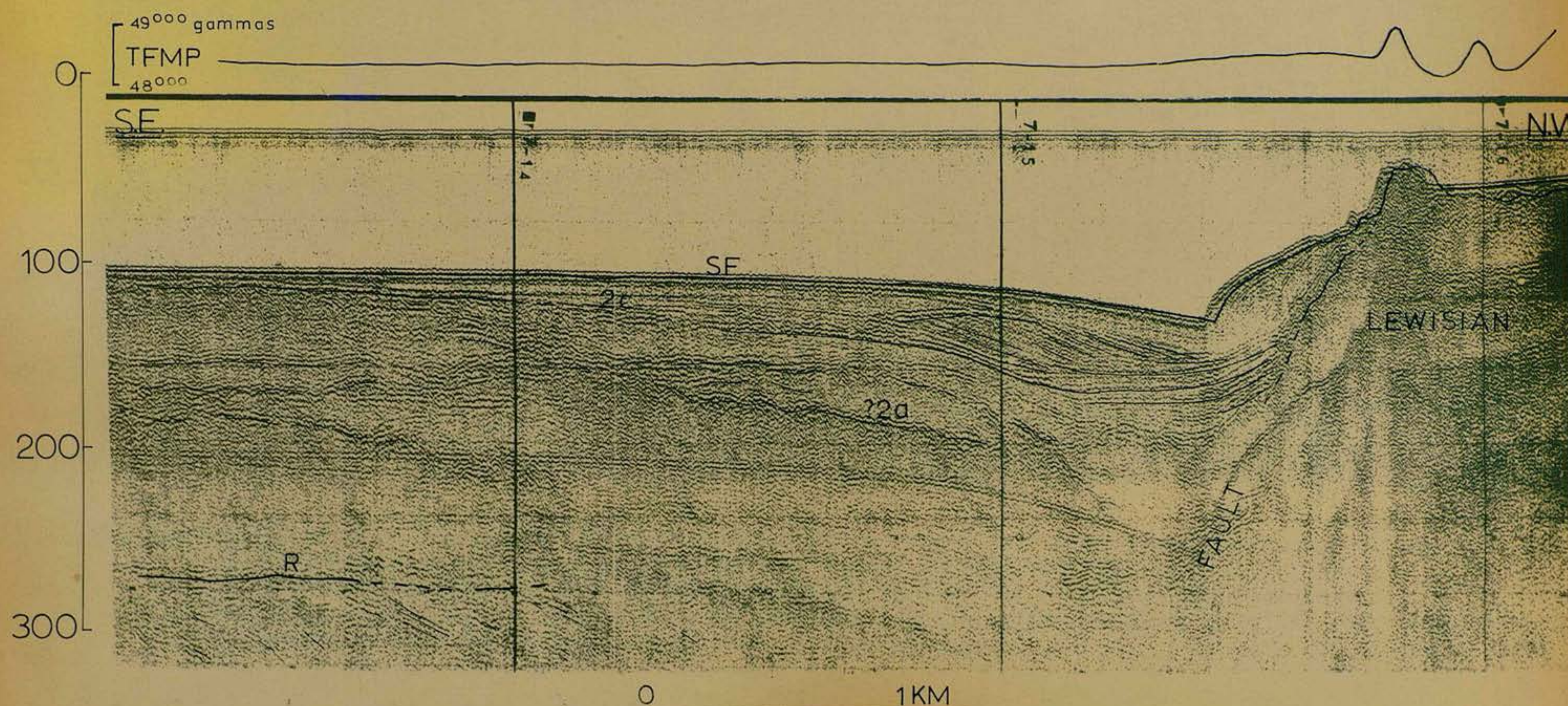



Fig.23. Shallow seismic and shipborne magnetometer profiles across the Camasunary-Skerryvore Fault south of Tiree. SF - Sea-floor; R - Rockhead; 2a - surface of Formation 2a; 2c - surface of Formation 2c; Vertical scale - two-way time in milliseconds. For location see Figs. 5 or 26.

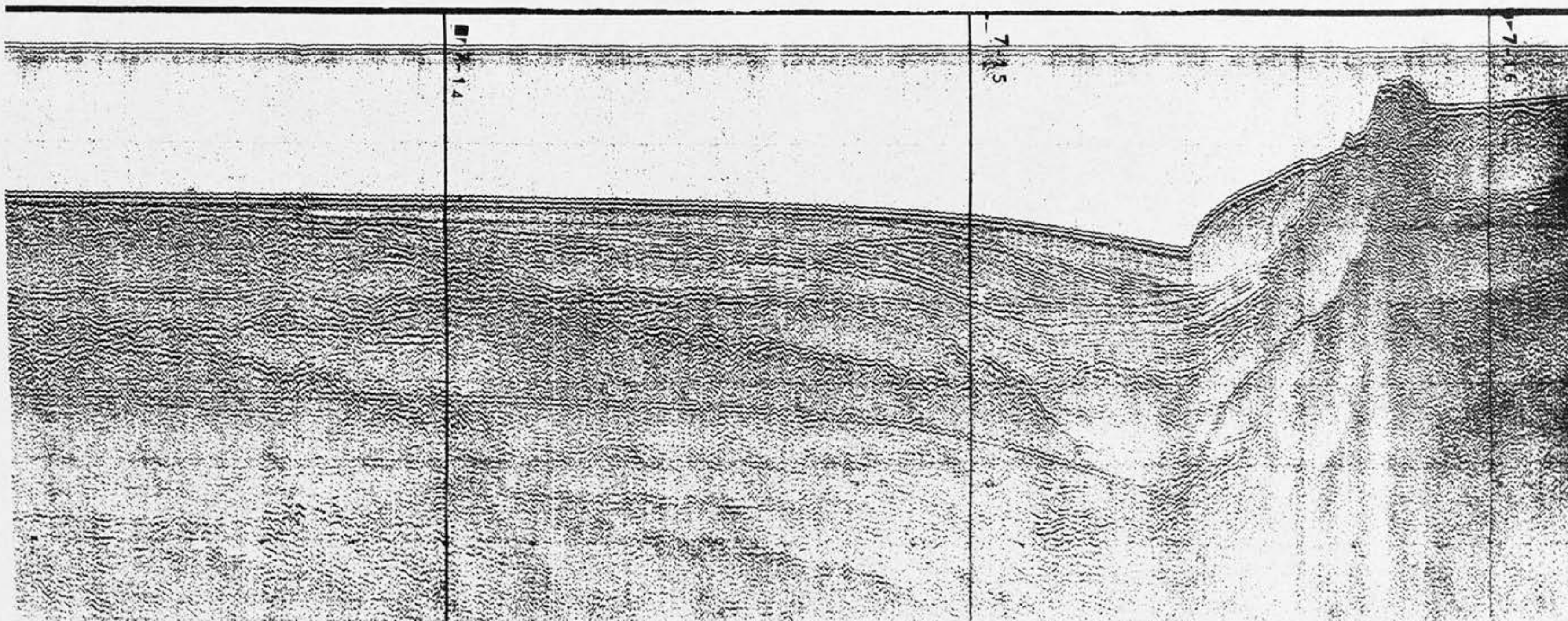


Fig.23. Shallow seismic and shipborne magnetometer profiles across the Camasunary-Skerryvore Fault south of Tiree. SF - Sea-floor; R - Rockhead; 2a - surface of Formation 2a; 2c - surface of Formation 2c; Vertical scale - two-way time in milliseconds. For location see Figs. 5 or 26.

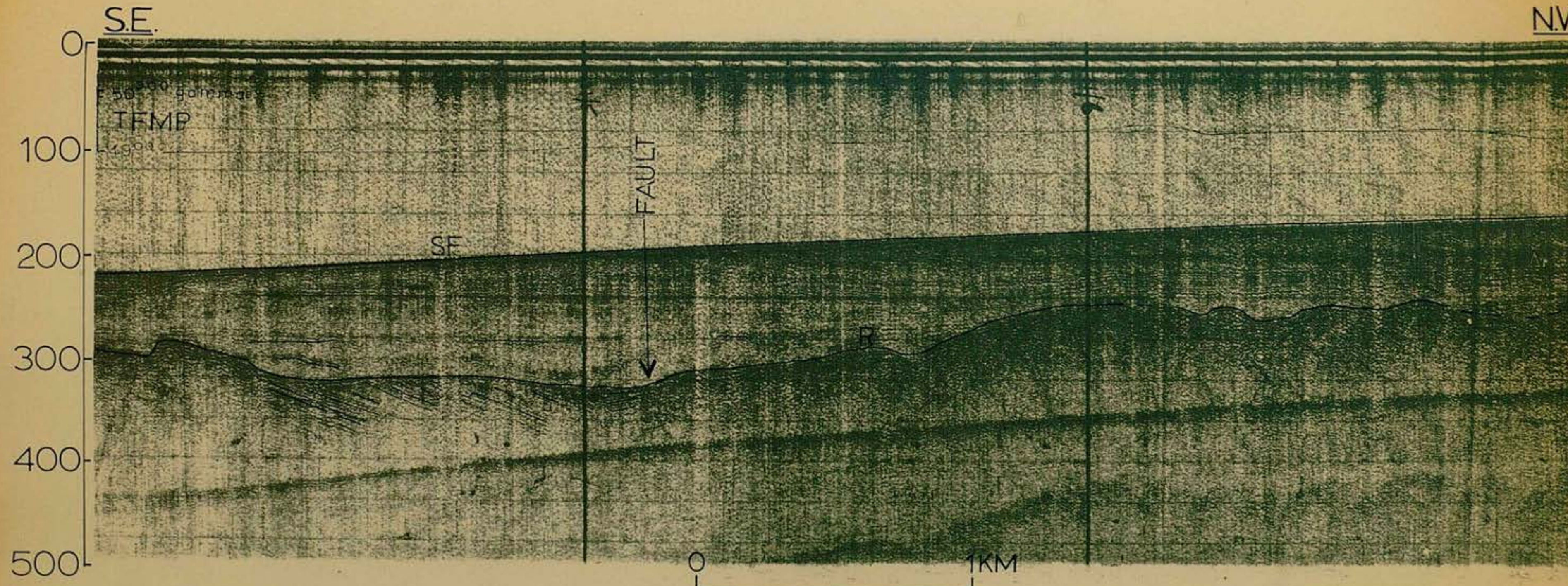



Fig.24. Shallow seismic and shipborne magnetometer profiles across the Camasunary-Skerryvore Fault west of the Blackstones Bank. Note the structureless texture of the lower part of the Quaternary (Formation 2c) sediments. Reflectors in the upper part of the Quaternary may represent Formation 3 sediments or sand beds in Formation 2c. For location see Figs. 5 or 26. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds.

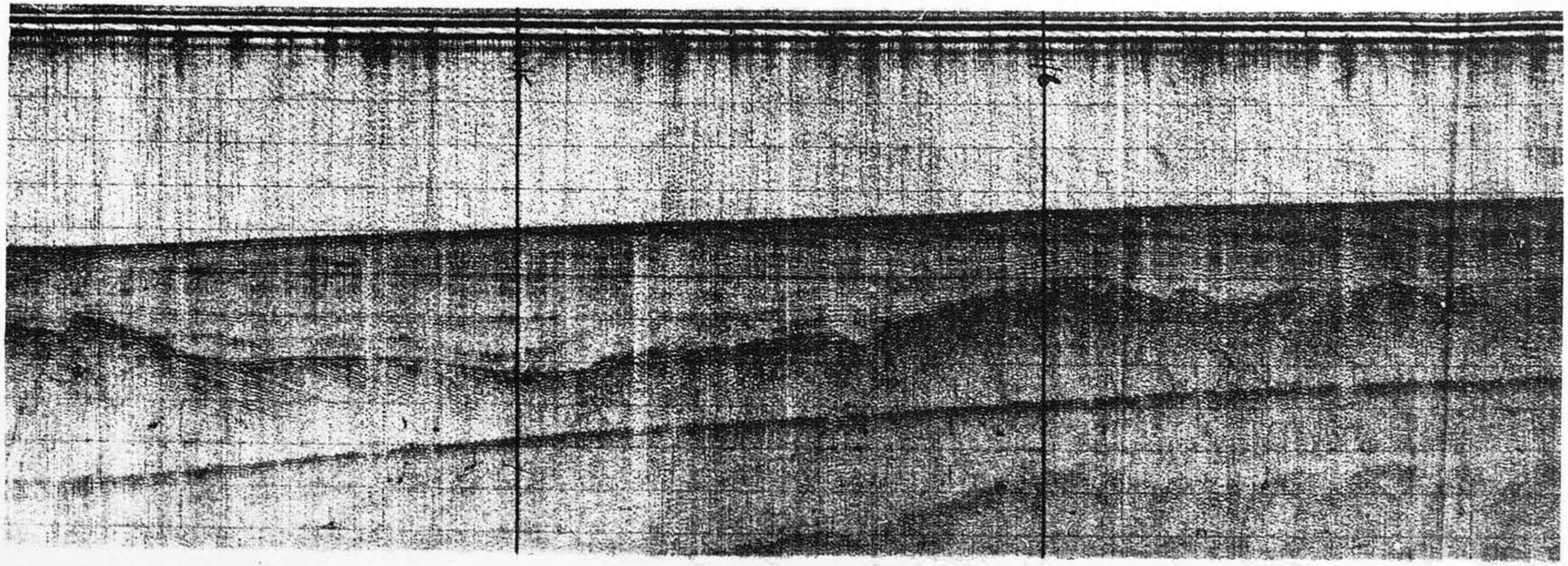


Fig.24. Shallow seismic and shipborne magnetometer profiles across the Camasunary-Skerryvore Fault west of the Blackstones Bank. Note the structureless texture of the lower part of the Quaternary (Formation 2c) sediments. Reflectors in the upper part of the Quaternary may represent Formation 3 sediments or sand beds in Formation 2c. For location see Figs. 5 or 26. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds.

seen on shallow seismic profiles. They are faulted against either the smooth surface of Domain 12d or the uneven surface of Domain 18 (Fig.24). Interference from the Blackstones Bank gravity anomaly obscures the gravity evidence between Skerryvore and Stanton Banks but a small gradient is apparent east of Stanton Banks.

Geology of the Inner Hebrides trough. The asymmetric structure of the Inner Hebrides Trough is clear from seismic and gravity evidence south and east of Coll and Tiree. The evidence for asymmetry from Skye and the Small Isles is as follows:-

(i) Some 13km east of the Camasunary Fault on Skye, Triassic and Liassic rocks rest unconformably on the Torridonian.

(ii) East of Eigg, bedded Jurassic (? Scalpa Sandstone) sediments of Domain 6 have been cored (borehole 72/6, Fig.33); the boundary between this domain and the Moine of Morar (Domain 24) does not appear as a fault and is therefore interpreted as a sub-New Red Sandstone unconformity similar to that seen on Skye and Ardnamurchan.

(iii) Mesozoic sediments crop out on Eigg and in the glacial trench to the west where they dip westwards into the Camasunary-Skerryvore Fault (Fig.22). At the fault these well-bedded sediments reach at least 320m below sea level.

East of Coll and Tiree the asymmetric structure of the trough is clear from the gravity map which shows a gravity low close to the coast. The sediments here are overlain by a cover of Tertiary lavas which crop out on the sea floor (Domain 3c).

The 15 mgal contour (taken as the eastern boundary of thick sediments - Fig.3) has a more westerly orientation at the south of the low. This coincides with a boundary on shipborne magnetometer and shallow seismic profiles between Domains 5d and 19 which has been interpreted as a fault. The Loch Assapol Fault is assumed to cross the head of Loch na Lathaich and enter the Ross of Mull granite on the west of the loch. The Moine crops out on the island of Inchkenneth, on the coast of the Ardmeanach peninsula and on the islet of Erisgeir; resistant rock, consistent with the Moine, is seen on a shallow seismic profile southwards from Erisgeir to borehole 72/9. The line of the fault between domains 5d and 19, therefore, if extended south-eastwards, would enter the Moine. I reject the possibility that this fault passes north-westwards through the centre of Domain 5d to connect with the fault through Gunna Sound; shipborne magnetic evidence clearly locates the fault north of Domain 19 and an abrupt change of direction is required to reorientate it towards Gunna Sound.

There is no clear evidence for the age of Domain 19; the rock is resistant and shipborne magnetic anomalies are variable. The aeromagnetic evidence indicates that the Lewisian rocks of Iona only extend a short distance to the west. The character of the shipborne magnet ometer profiles suggest that the anomalies may be caused by intrusion of basic igneous rocks into resistant sediment and the domain is therefore tentatively interpreted as Torridonian to Upper Palaeozoic sediment. If this is so then the western margin of trough basement outcrop has been moved by the fault which forms its northern margin.

The south-western margin of this basement domain, 19, is not obviously fault controlled (on morphological evidence only).

It has been traced past Domain 19 to Domain 22 where it intersects the Great Glen Fault.

Domain 5d has Mesozoic seismic character with well-developed bedding. A deep reflection profile (Profile 2, Seismograph Service Ltd., 1970) across the trough shows its asymmetry. Contrary to the interpretation in Binns and others (1974a) the strong reflector cropping out as a scarp on rockhead has been shown by drilling (borehole 72/12, Appendix 2) to be a dolerite sill and not trough basement. East of the outcrop of these sills however the sedimentary rocks, as evidenced by their closely-spaced steep bedding and more resistant surface, have a different character and could be Palaeozoic sediments (Domain 14). The geology of this area and of Domain 8, where shallow seismic penetration does not reach rockhead, is poorly understood. Tertiary sediments may be present. A deep reflection profile (Fig.10), however, which crosses the Blackstones Plutonic Centre (McQuillin, Bacon and Binns, in preparation), shows the igneous body to be in contact with undisturbed sediments and the authors therefore suggest a Tertiary age for these.

The Blackstones Centre itself, (Domain 1b) crops out (Fig.25) and has been sampled (SH579 and SH 776, Appendix 2). Interpolation of its boundary between shallow seismic and shipborne magnetometer profiles is based on bathymetric evidence. A north-south fault, the eastern margin of Domain 31c, is conjectured to extend southwards through a bathymetric depression dividing the centre.

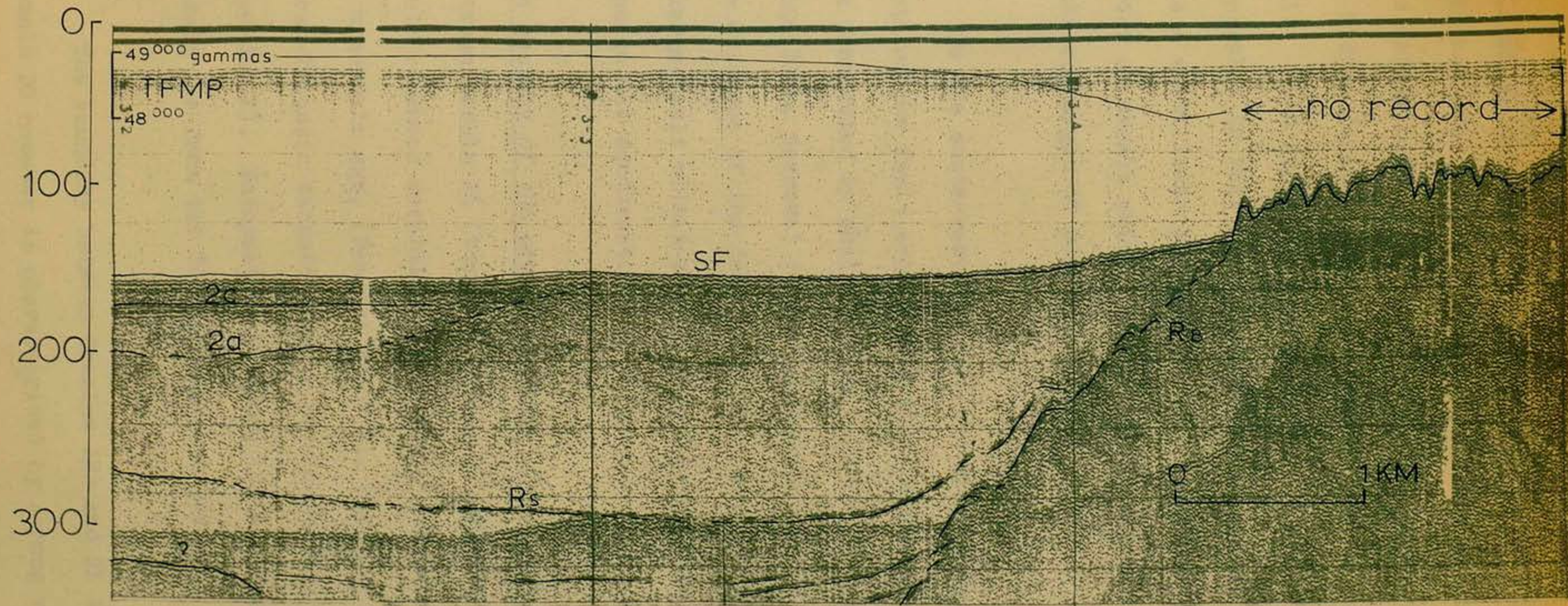



Fig.25. Shallow seismic and shipborne magnetometer profiles across the southern margin of the Blackstones Bank. For locations see Figs 5 or 26. A weak reflector, Rs, is interpreted as the top of Pre-Quaternary sediment: this unit appears to be upturned against the surface of the Blackstones Pluton ($R_B$). SF - Sea-floor; 2a - surface of Formation 2a; 2c - surface of Formation 2c. Vertical scale - two-way time in milliseconds.

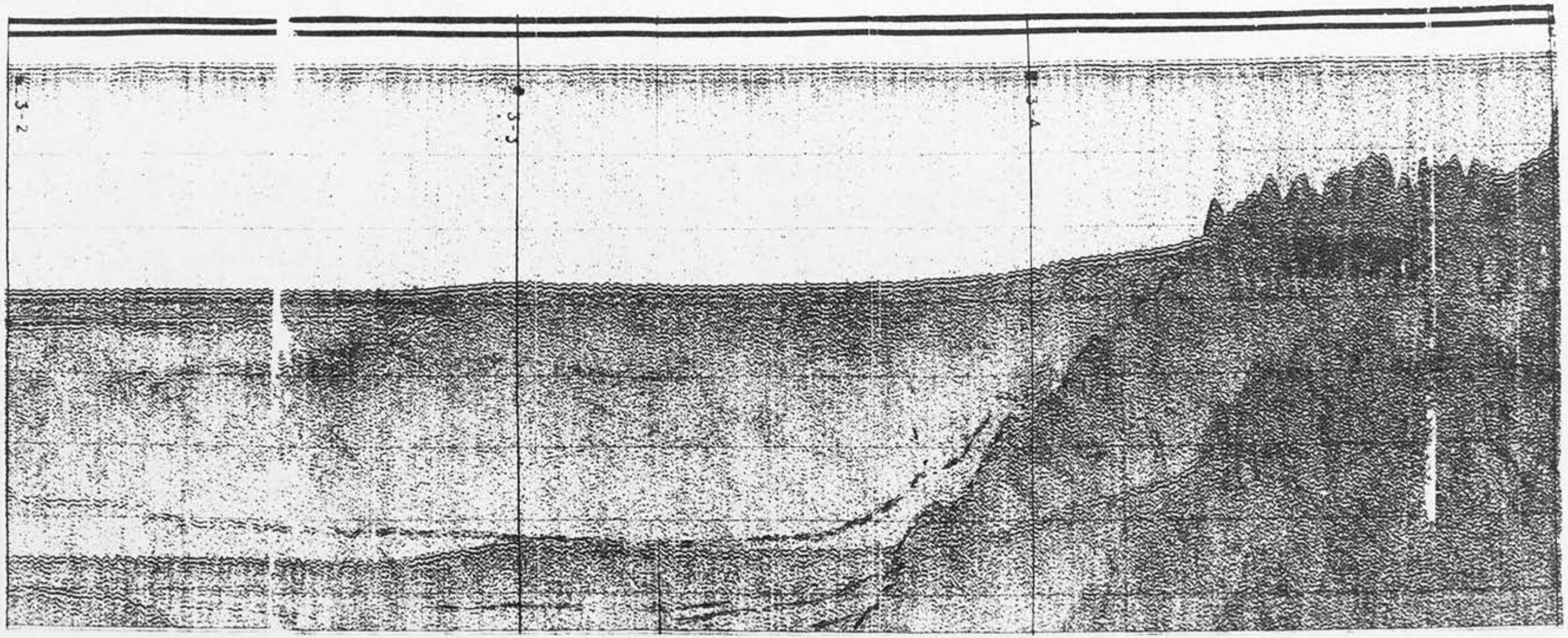



Fig.25. Shallow seismic and shipborne magnetometer profiles across the southern margin of the Blackstones Bank. For locations see Figs 5 or 26. A weak reflector, Rs, is interpreted as the top of Pre-Quaternary sediment: this unit appears to be upturned against the surface of the Blackstones Pluton ($R_B$). SF - Sea-floor; 2a - surface of Formation 2a; 2c - surface of Formation 2c. Vertical scale - two-way time in milliseconds.

### 2.2.5. Great Glen Fault and area to south-east.

The line of the Great Glen Fault. The Great Glen Fault (Kennedy, 1946) has been traced to Loch Buie on the south **coast** of Mull (Lee and Bailey, 1925). Cenomanian sediments lie unconformably on the Middle Jurassic east of the fault and on the Lias west of the fault. This suggests late Jurassic or early Cretaceous movement comparable to that on the Camasunary Fault (p8). South-west of Loch Buie a rectilinear gradient on the aeromagnetic map coincides with a series of shoals which terminate in a rectilinear scarp, the southern margin of Domain 22 (Fig.2).

To the south-west the less resistant rocks of Domain 8 lie north of the fault and erosion has lowered rockhead to a level not penetrated by shallow seismic profiles. The gravity map (McQuillin, personal communication) however is consistent with the evidence of the deep reflection profile in Fig.10. This shows a large fault within acoustically featureless sediments, throwing down to the southeast.

The geology of the area south-east of the Great Glen Fault. Between Domain 26 (the Torridonian of Colonsay) and the Great Glen Fault rockhead morphology and gravity indicate a sedimentary trough of uncertain age, (Domains 9 and 11, Fig.9). East of Colonsay red Permo-Triassic sandstones have been cored (boreholes 71/9 and 73/25, Appendix 2). Bathymetric evidence indicates that a fault separates Domain 12e from the Torridonian of Colonsay.

The boundary between domains 12e and 21 is poorly defined. Domain 20 however is characterised by strong relief (Fig.2) and is interpreted as the offshore continuation of the Dalradian of Lorne.

# CHAPTER 3

# DESCRIPTION OF QUATERNARY GEOLOGY

## 3.1. EVIDENCE AND METHOD OF INTERPRETATION

It has been shown above (p.17) that on the inner continental shelf (east of 08°00'W) there is a rockhead reflector with a characteristically glacial morphology. In this area therefore the sedimentary layer above this reflector is of Quaternary age: on the outer continental shelf rockhead has not obviously been glacially eroded and so the possibility that Tertiary sediments lie above it can not be excluded. In this chapter the morphology of rockhead is discussed and the sedimentary layer above it is interpreted.

A rockhead map (Fig.4) has been prepared using the method described on page 17. Interpretation of the sediment layer above it is made in two stages. Firstly shallow seismic profiles (sparker and pinger) are analysed. Secondly this analysis is calibrated by cores, and boreholes drilled from an anchored ship: the method is similar to that used to interpret pre-Quaternary geology except that only the seismic technique is used and the geophysical 'Domains' to be calibrated are layers with characteristic seismic textures and not areas on rockhead. Little calibration by drilling has yet been done.

The evidence considered in this interpretation is as follows:-

3.1.1. Geophysical evidence. Shallow seismic profiles. Shallow seismic profiles have been used in three ways:-

(i) Together with bathymetric evidence they have been used to map out the glaciated morphology of rockhead (Fig.4 and p.17).

(ii) They have been used to map out total thickness of Quaternary sediment (Fig.26). Thicknesses have been measured from the profiles assuming a seismic velocity of 1.8km/sec. Interpolation of isopachytes between lines is controlled by the need for consistency with bathymetric and rockhead contours.

(iii) They have been used to subdivide the Quaternary layer on the basis of seismic texture.

3.1.2. Geological evidence. Land geology. A summary of the Quaternary land geology is given in the introduction (p.10). It can not be used to calibrate geophysical data as is the case with the pre-Quaternary geology: instead it provides important background information.

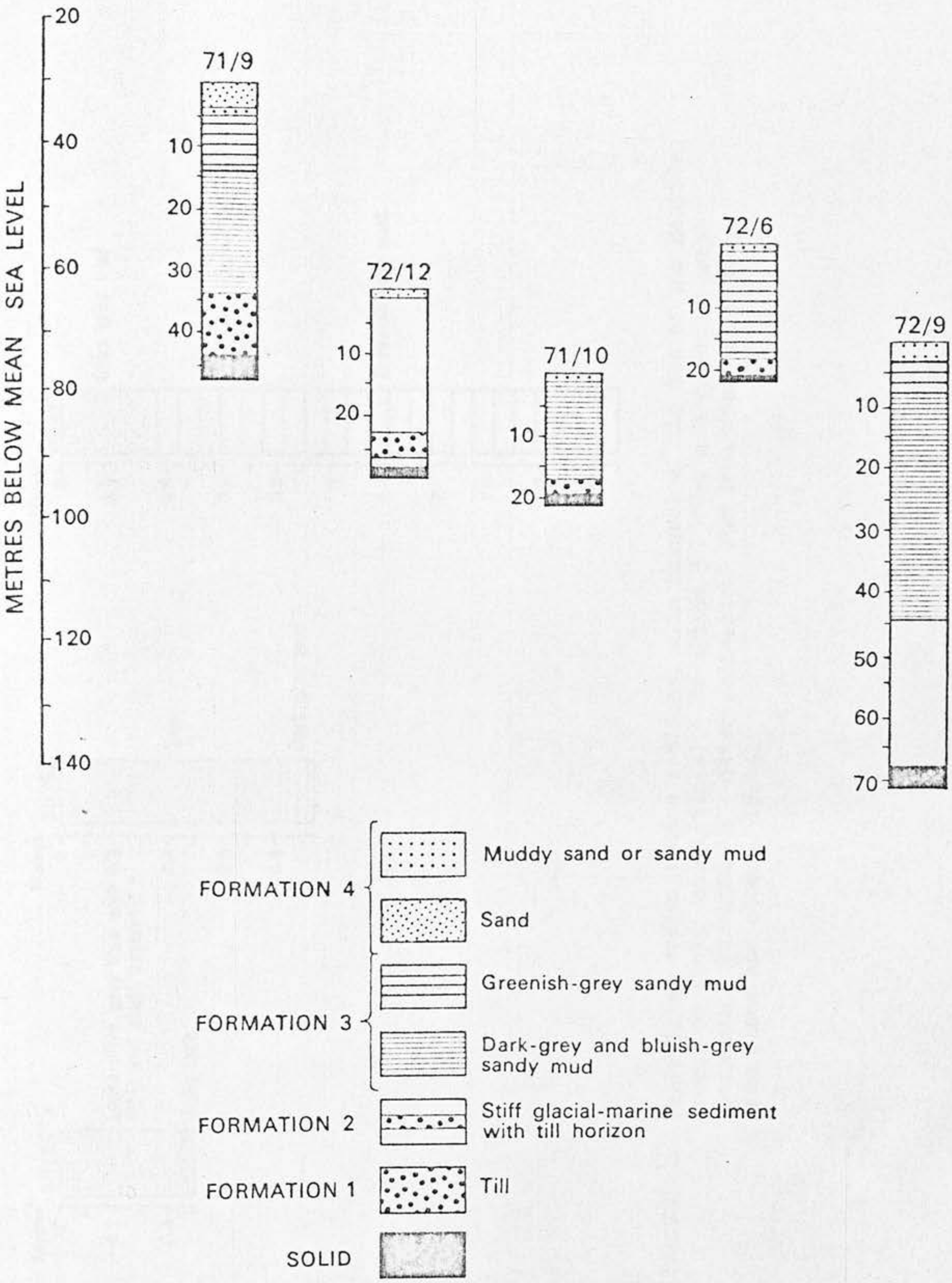
Off-shore sampling. The following sets of samples have been recovered:-

1. Five boreholes drilled by MV Whitethorn have recovered Quaternary sequences up to 68m thick. Either shell and auger or wireline methods were used and samples were taken at vertical intervals of 2m where recovery allowed this. During shell and auger drilling, care was taken to ensure that the sample was taken from the centre of each core of fresh sediment.

2. Sea-floor sediment was sampled along the IGS reconnaissance grid at five nautical mile intervals and also along selected traverses crossing trenches and banks at right angles to the strike of the topography (Binns and others, 1974a, Fig.11). At each station surface and core samples were taken using a Shipek Grab and either a vibrocorer, a gravity corer (both fitted with transparent plastic tube) or, where the sediment was firm, a simple steel tube.

The colour of this sediment was noted by reference to the Munsell Soil Colour Chart and the stratigraphy of the cores measured on recovery.

In this study I have used the boreholes (Fig.27) to calibrate the shallow seismic profiles and thus to erect a simple litho-stratigraphy of three sedimentary formations. Information about an upper, fourth formation, too thin to be resolved by seismic profiling, is provided by the shallow cores (Figs. 28-30). Initial laboratory results are presented as evidence for a first hypothesis to explain the history of sedimentation. No attempt has been made to undertake a detailed sedimentological study on the material.




ig.27. Boreholes through Quaternary sediment. For locations see Fig.26.
From Binns and others, 1974b.

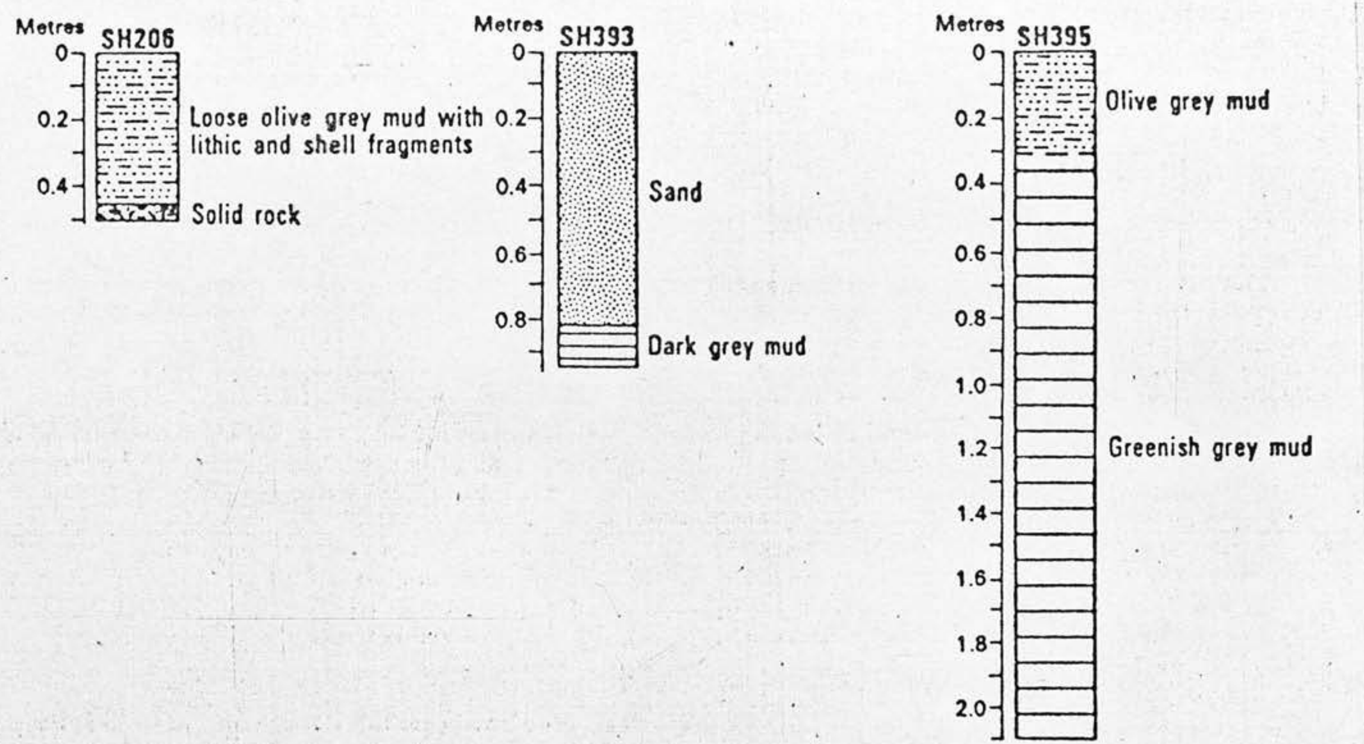



Fig.28(a). Superficial sediment core sections, main channel of the Sea of the Hebrides (based on field descriptions). Formation 3 - Dark and greenish grey sediments. Formation 4 - other sediments. For locations see Fig.26. From Binns and others, 1974a.

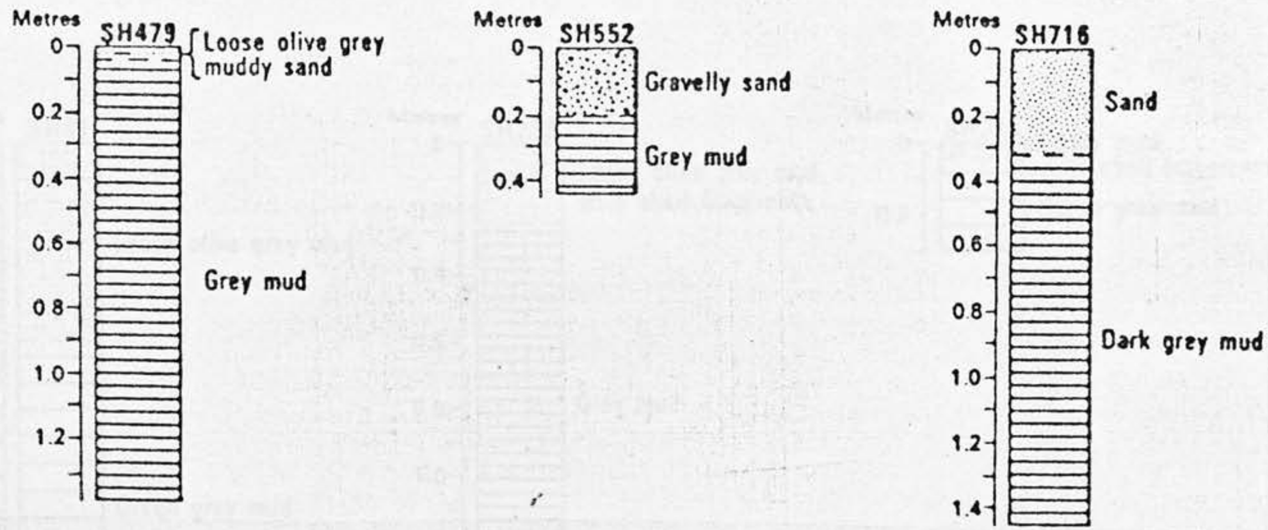



Fig.28(b). Superficial sediment core sections, main channel of the Sea of the Hebrides (based on field descriptions). Formation 3 - Dark and greenish grey sediments. Formation 4 - other sediments. For locations see Fig.26. From Binns and others, 1974a.

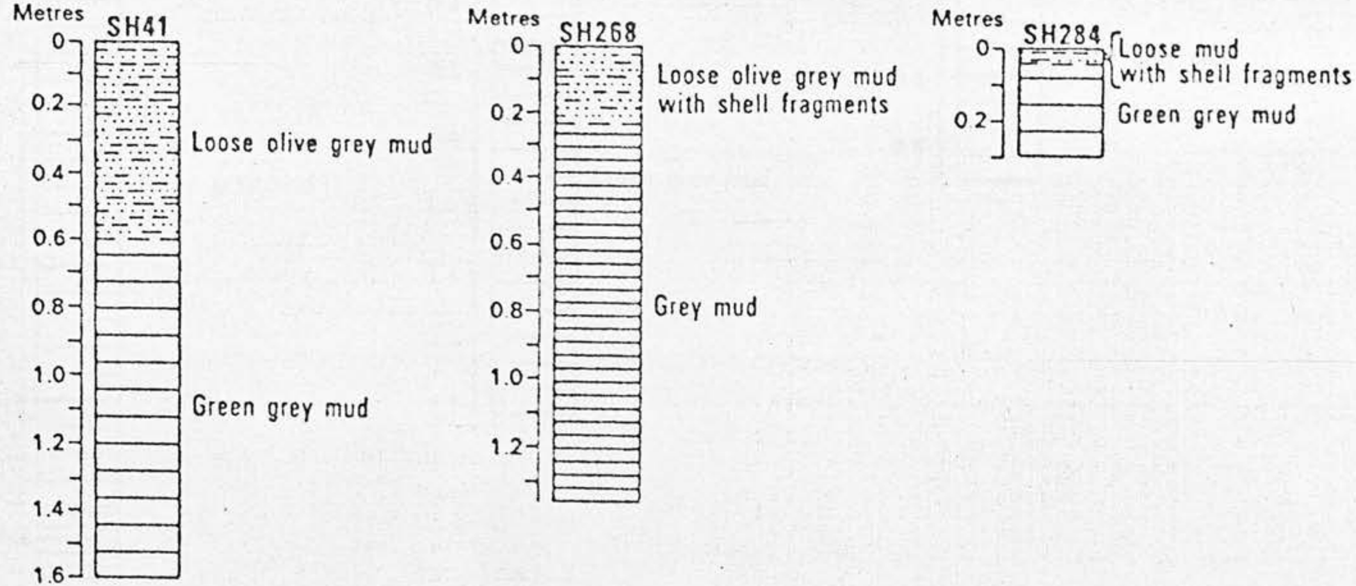



Fig.29(a). Superficial sediment core sections. Inner Hebrides (based on field descriptions). Formation 3 - Dark grey and green grey muds: Formation 4 - other sediments. For locations see Fig.25. From Binns and others, 1974a.

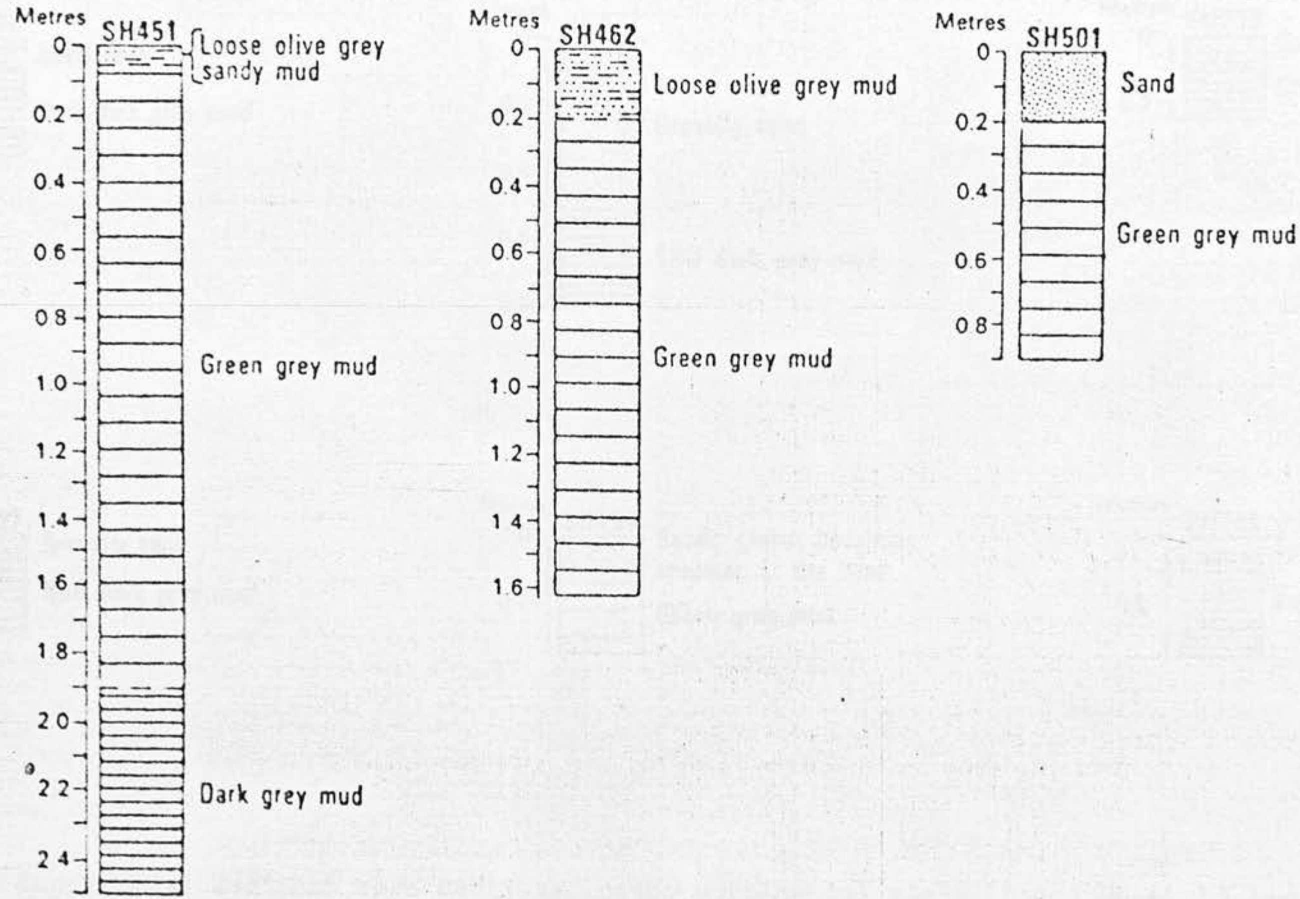



Fig.29(b). Superficial sediment core sections, Inner Hebrides (based on field descriptions). Formation 3 - Dark grey and green grey muds: Formation 4 - other sediments. For locations see Fig.26. From Binns and others, 1974a.

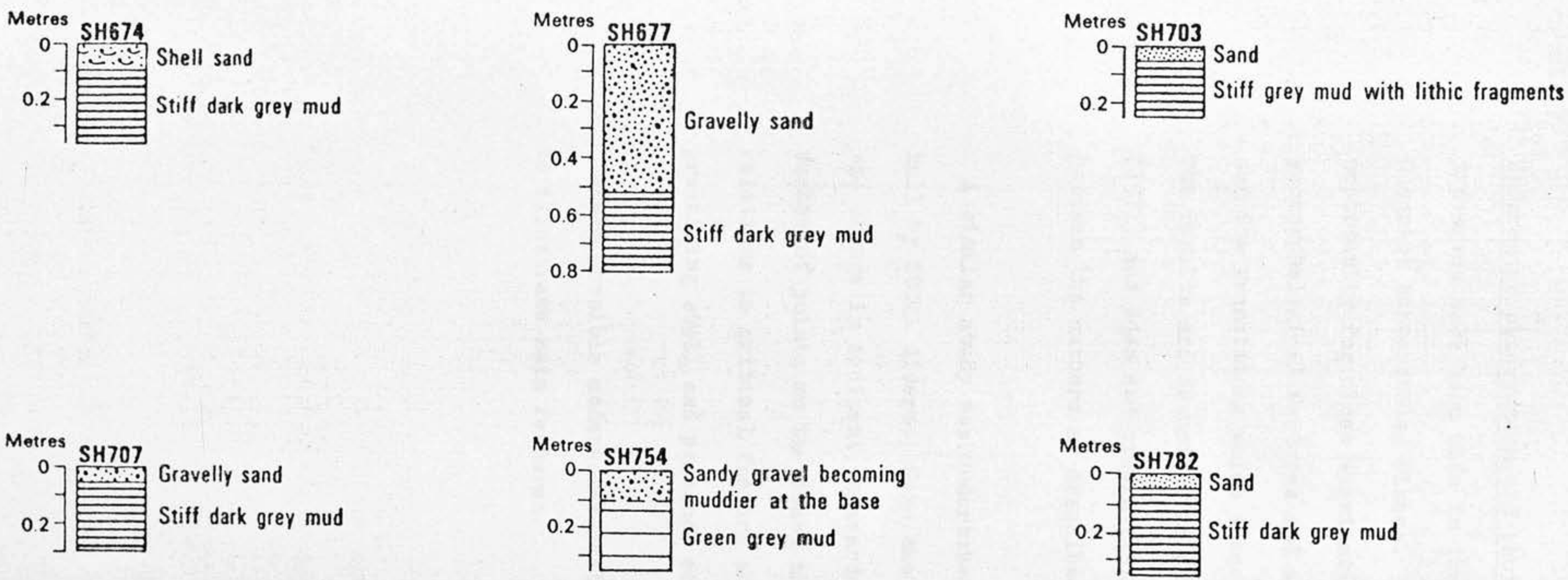



Fig.30. Superficial sediment core sections, outer continental shelf (based on field descriptions). Formation 2 - stiff muds. Formation 3 - green grey muds. Formation 4 - other sediments. For locations see Fig.26. From Binns and others, 1974a.

Underwater observation and photography. Twenty traverses have been made in the area by the Vickers Oceanics' submersible, Pisces. The work provided an opportunity for close examination of representative geomorphological features and sedimentary environments and the transitions which take place between them. The results are described in detail in Eden and others (1971) and Eden and others (1973): the work was shared between the authors as described in the prefaces.

A similar study was undertaken around the coasts of Mull by SCUBA divers. Here the objective was to examine the change in sediment, seawards from the beach, at a number of points on the coast which differed in their relations to critical factors such as the direction of prevailing swell and presence of rock outcrop offshore.

Where possible underwater photographs were taken to illustrate main features.

## 3.2. DESCRIPTION

### 3.2.1. Glacial erosion.

The rockhead map (Fig.4) clearly shows a number of major, enclosed rock basins. A comparison of rockhead morphology with Pre-Quaternary geology (Binns and others, 1974a, Fig.2) shows that the locations of these basins are controlled by one or more of three factors:-

(1) Proximity to high ground (for example the Tertiary centres of Mull and Skye).

(2) The presence of less resistant formations (for example the Mesozoic sediments of the Troughs).

(3) The presence of lines of weakness within areas of igneous or metamorphic rocks (for example the Great Glen).

A striking feature of the map is the trench running south-west from Rhum. Almost completely filled with Quaternary sediment (Figs.26 and 31) its presence was never previously suspected, attention having been concentrated on the line of hollows close to the Outer Hebrides (Ting, 1937, Sissons, 1967, p.52). It is controlled by the resistant 'Horizon A' (p.44) and "diverted" westwards by it to terminate in a deeper basin in front of the Minch Fault scarp.

This feature draws attention to the danger of deducing the location of rock basins from bathymetric evidence. Irregularly distributed Quaternary sediment obscures many basins and displaces the deepest parts of others (Fig.31).

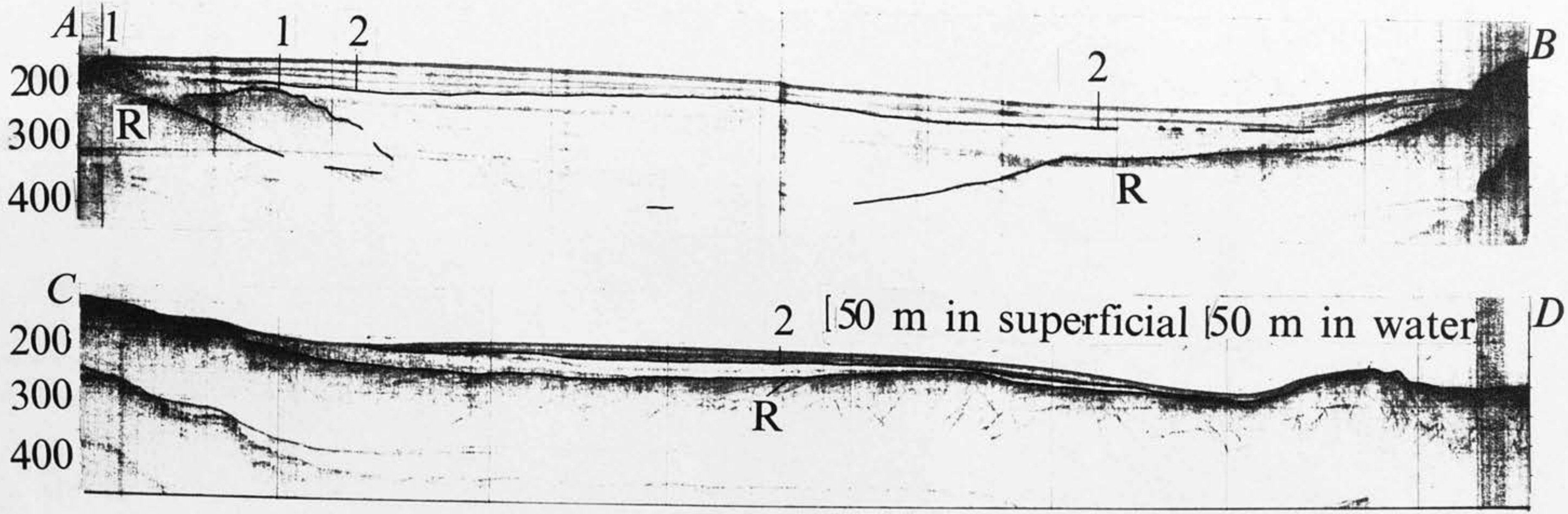



Fig.31. Sections A-B and C-D. Interpreted shallow seismic profile. R - Rockhead; 1 - Surface of Formation 1; 2 - Surface of Formation 2; Vertical scale - two-way time in milliseconds. For location see Fig.26. From Binns and others, 1974b.

A second notable series of trenches runs from Mull, westwards to the scarp of the Camasunary-Skerryvore Fault, then southwestwards to the Blackstones Bank. East of the Blackstones Bank rockhead is not seen on shallow seismic profiles.

Underwater observation (Eden and others, 1971) confirms the glaciated nature of rockhead morphology, On four dives the submersible climbed up the steep rock walls of a U-shaped valley (op.cit. Figs 6,11,15): the shoals crossed have glacially smoothed or plucked rock surfaces (op.cit. plate 5b and 6a).

3.2.2. Quaternary sediments - inner continental shelf.

Within the Quaternary sediment layer cores and boreholes have recovered lithologies which have been assigned to four formations (Figs.26-29). Evidence presented below suggests that three of these formations produce a characteristic texture on shallow seismic profiles (variable density display). The profiles therefore have been used to map out the thickness and distribution of each of the formations thus providing important evidence for the origin of each formation (Fig.26).

Formation 1 - Till. Till constitutes only a small proportion of the sediment column encountered in the boreholes. Reflections from the surface of moraine hummocks are seen on some shallow seismic profiles (Fig.31 and Fig.16) but more commonly the profiles fail to record a boundary between Formations 1 and 2. This may be due to lack of velocity contrast between Formations 1 and 2 or to an insignificant thickness of Formation 1.

Loose morainic debris of Formation 1 is present on rock shoals, (Eden and others, 1971, Plate 6b).

Formation 2a. South of Tiree and south of the Blackstones Bank a strong reflector separates sediment with the character of the sampled Formation 2c from a lower unsampled layer with a characteristic surface (Figs. 23 and 25). This lower layer does not have the seismic texture of till and has therefore been tentatively assigned to Formation 2.

Formation 2b. Locally (Fig.26) well-bedded sediment lies beneath Formation 2c. Its seismic character however is different from that of Formation 3 and it also has been tentatively assigned to Formation 2 (cf similar sediments in the North Sea, Binns and others, 1974c).

Formation 2c. These sediments have been sampled in boreholes 72/9 and 72/12. Because of their firmness only one sample from each section was recovered but drillers logs indicated sediments of similar character over the intervals shown on Fig.27.

The sediments are very firm, poorly sorted "sandy muds" (Folk, 1968) containing variable amounts of granule and pebble grade lithic fragments. There is no 'rock flour' (Basham and Morgan, 1973).

Benthonic foraminifera are sparse (M. J. Hughes, personal communication) but there is a significant dinoflagellate cyst population dominated by a cold water species (Harland, R. in Binns and others, 1974a and 1974b).

Poor seismic record quality across borehole 72/9 prevents correlation of seismic texture and lithology.

In borehole 72/12 Formation 2 sediment is clearly associated with a distinctive seismic texture (Fig.32). Widely spaced but continuous reflectors are separated by structureless intervals.

Formation 3. Sequences assigned to Formation 3 were recovered from boreholes 71/9, 71/10, 72/6 and 72/9 (Fig.27) and most shallow cores penetrated modern (Formation 4) sediments into this formation (Figs 28-29). A pilot study has been made of the sequence in borehole 71/9. The sediments are green-grey or grey, poorly-sorted "sandy muds" or "muddy sands" (Folk, 1968) with a mineralogy similar to that found in Formation 2 (Basham and Morgan, 1973). In contrast to Formation 2, however, the sediments are plastic and contain medium sand to pebble grade fragments only rarely and then at levels coinciding with cold-water faunal assemblages. Green-grey sediments always overlie blueish-grey or dark-grey sediments.

Study of the foraminifera and organic-walled microplankton in Borehole 71/9 by Harland (1974) and Hughes (1974), has shown that this Formation 3 sequence can be divided into three palaeoclimatic zones. The foraminiferal population recovered from 30m to 28m is dominated by Ammonia batavus (Hofker), a warm, shallow-water species. A rich assemblage of dinoflagellate cysts, dominated by Peridinium spp. (54.2%), appears to indicate a similar environment. In contrast a cold-water assemblage of foraminifera dominated by Elphidium clavatum Cushman is present between 26m and 16m and is consistent with the presence of the isolated (? ice-rafted) pebbles. The poor recovery of dinoflagellate

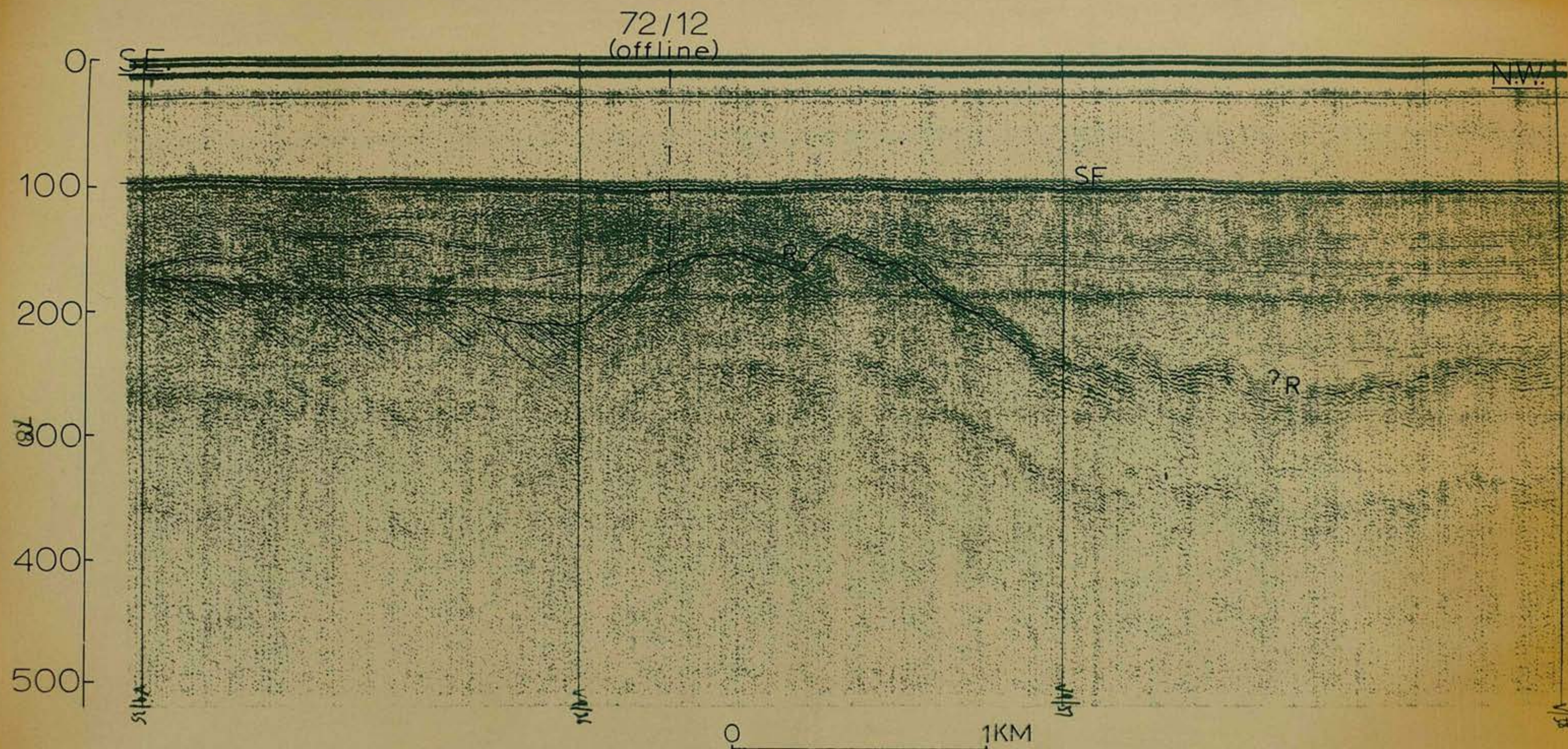



Fig.32. Shallow seismic profile across borehole 72/12. For location see Figs. 5 or 26. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds. Formation 2c sediments overlie rockhead (a Tertiary sill intruded into sediments) and exhibit a structureless texture broken by continuous reflectors.

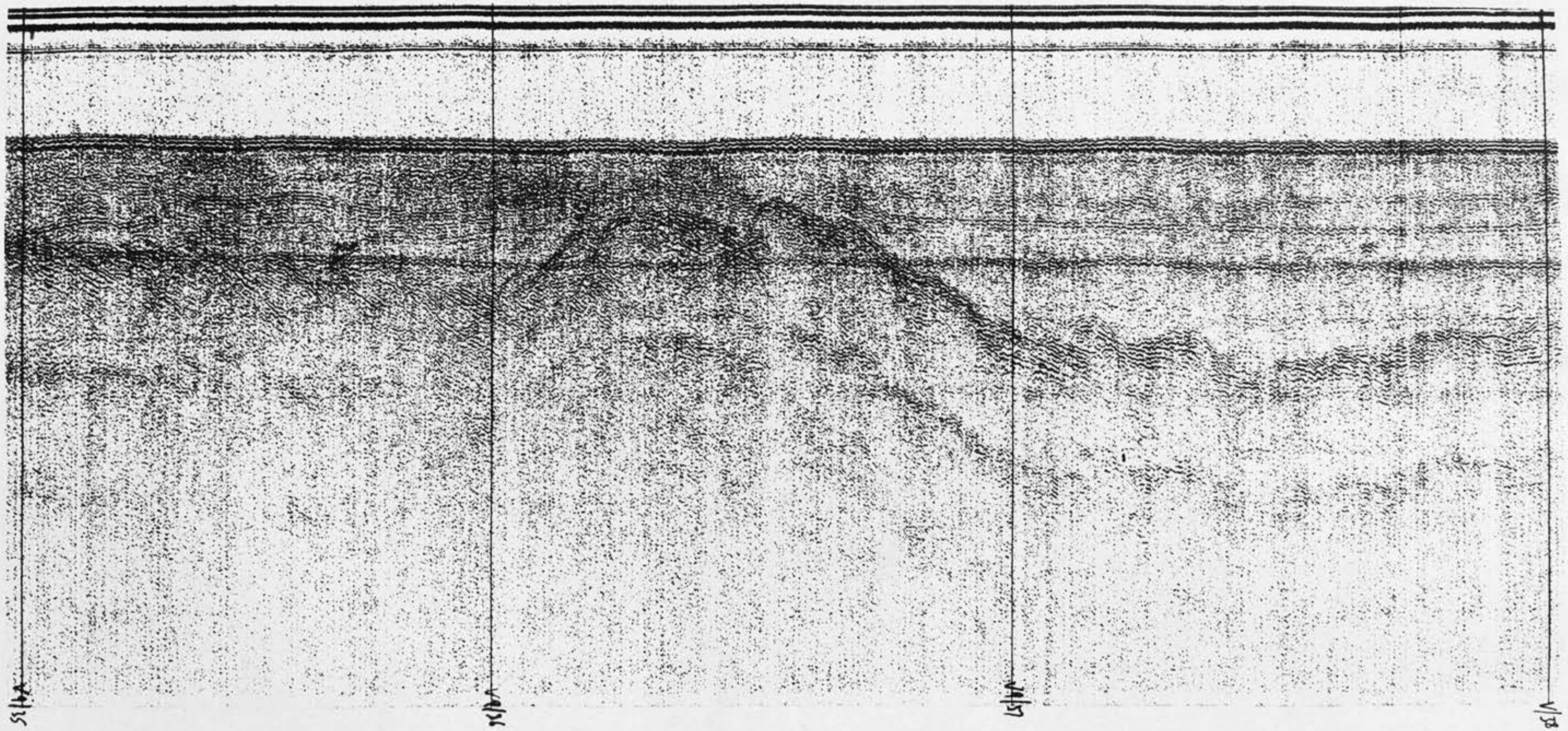


Fig.32. Shallow seismic profile across borehole 72/12. For location see Figs. 5 or 26. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds. Formation 2c sediments overlie rockhead (a Tertiary sill intruded into sediments) and exhibit a structureless texture broken by continuous reflectors.

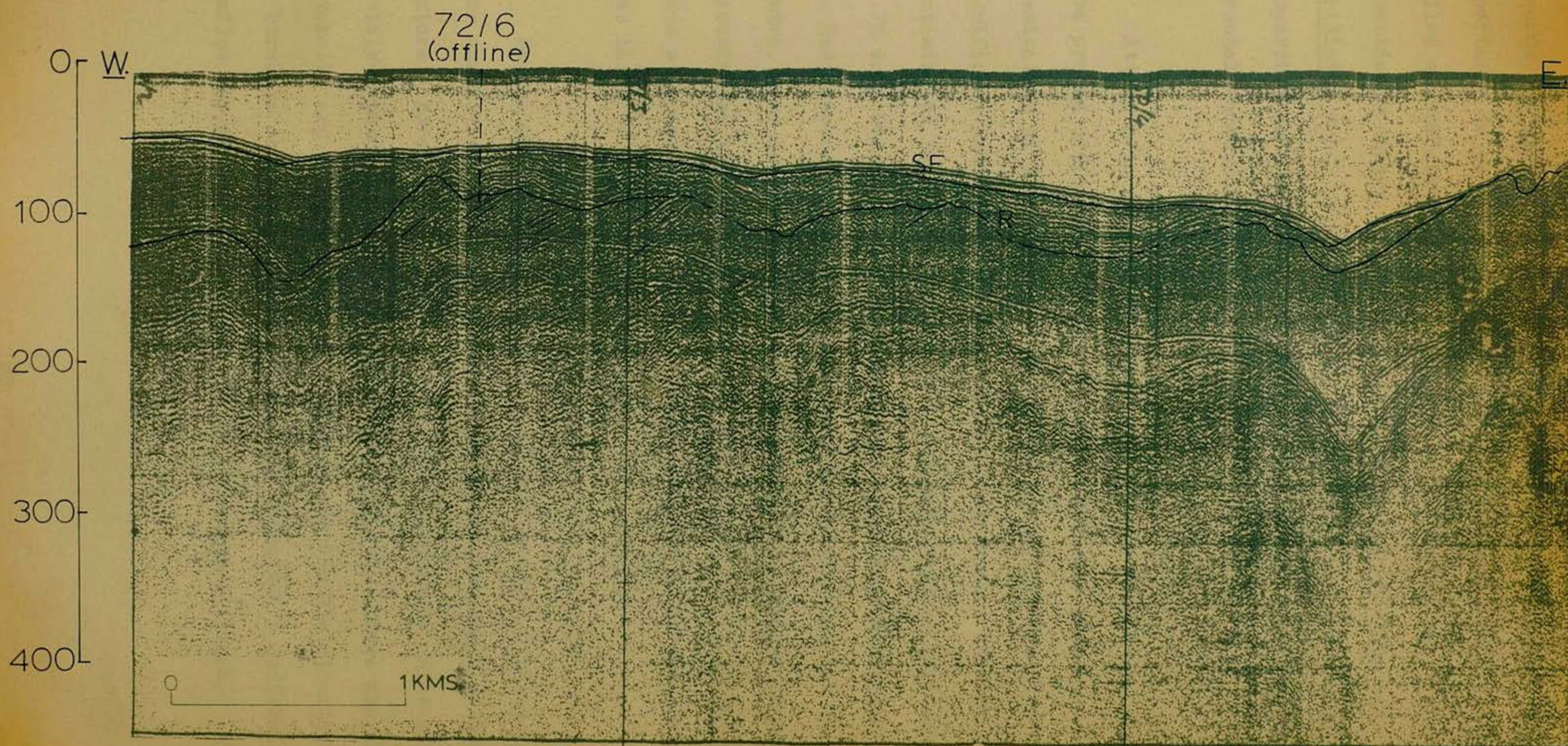



Fig.33. Shallow seismic profile across borehole 72/6. For location see Figs. 5 and 26. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds. Bedded Quaternary (Formation 3) sediments lie above Rockhead.

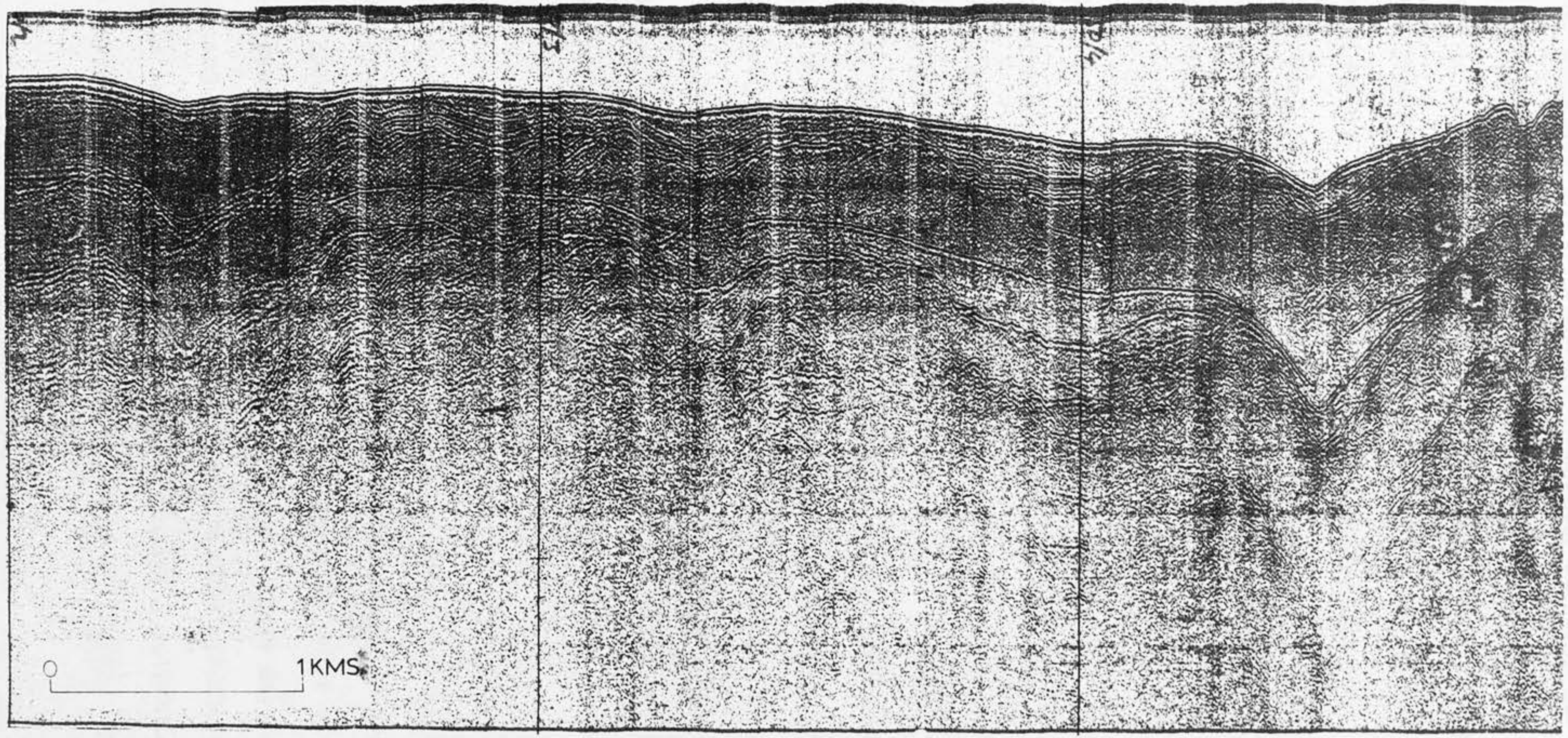



Fig.33. Shallow seismic profile across borehole 72/6. For location see Figs. 5 and 26. SF - Sea-floor; R - Rockhead; Vertical scale - two-way time in milliseconds. Bedded Quaternary (Formation 3) sediments lie above Rockhead.

cysts from these samples is discussed in Chapter 4. From 14m upwards, E. clavatum and other cold-water species decline in importance to be superseded by a warm-water fauna. The organic-walled microplankton from 10m to the top of the borehole are essentially modern in aspect (dominated by Spiniferites and Peridinium spp., up to 85% of the assemblage) and are closely comparable to modern sea bed samples in the area (Harland, R., personal communication).

Attempts to date the sequence in borehole 71/9 using radiocarbon have proved difficult. No large shells have been found and examination of the disseminated organic matter has revealed significant amounts of reworked Mesozoic material. The least contaminated sample was at 6m; of the organic-walled microplankton 14.7% were Mesozoic forms and amorphous organic matter appeared fresh. The Radiocarbon Dating Laboratory of the Scottish Reactor Research Centre, East Kilbride obtained a date of 9,961 $\pm$ 250 BP from the disseminated organic matter in the sample (SRR 117). It has been taken as a maximum date which reduces to 8,680 BP on the assumption that 14.7% of the carbon is "dead".

Boreholes 71/9 and 72/9 both calibrate seismic profiles of poor quality and it is not possible to relate lithology to seismic texture. Boreholes 71/10 and 72/6 however penetrate units with closely-spaced horizontal reflectors (Fig.8,33). These may fade laterally and can not be correlated with any visible structure in borehole sediments. West of Colonsay Formation 3 sediments fill shallow depressions on the surface of Formation 2 (Fig26). In contrast, east of Colonsay, an area protected from the prevailing south-westerly swell, nearly 30m of Formation 3 sediments have been deposited and preserved at a topographically higher level ( cf boreholes 71/9 and 72/12, Fig.27). Formation 3 sediments also occur in the trench north-west of Coll (Fig.31) and in the glacial trenches around Inner Hebridean islands.

Formation 4 - Modern sediment. Here 'modern' implies that the sediment was deposited or reworked by, and therefore is in equilibrium with, the present marine regime.

These sediments are coarse, shelly sands and gravels and soft, olive-grey muddy sediments. They form a thin (0.05m to 2.0m) layer on all older formations (Figs.28-29; Eden and others, 1971, Plate 6b). In this area therefore they are probably not detectable on seismic profiles (but see Fig.25).

There is a field description and sediment distribution map in Binns and others (1974a).

### 3.2.3. Quaternary sediment - outer continental shelf.

On the outer continental shelf the sea floor is relatively flat but the rockhead reflection drops evenly westwards giving rise to a seaward-thickening sediment cover. Penetration to rockhead was not achieved west of 08°30'W. No large scale glacial erosion forms are evident on rockhead and so the possibility that Tertiary sediment forms part of the uppermost seismic layer cannot be excluded.

Seismic reflectors within this layer are sub-horizontal and the texture is comparable to that of Formation 2. Two reflectors have been traced over the outer shelf and onto the slope (Fig.34). On the shelf they maintain depths of 130-160m and 190-220m respectively beneath mean sea level and they parallel the sea floor at the top of the continental slope. In places the sea floor falls to intersect the upper reflector.

Short ( 0.8m) cores taken at the outcrop of the lower unit penetrated a thin (0.1m to 0.5m) cover of Formation 4 sands and gravels to recover Formation 2 sediments (Fig.30).

Traverses with the submersible Pisces on the continental slope and outer shelf are described in Eden and others (1971).

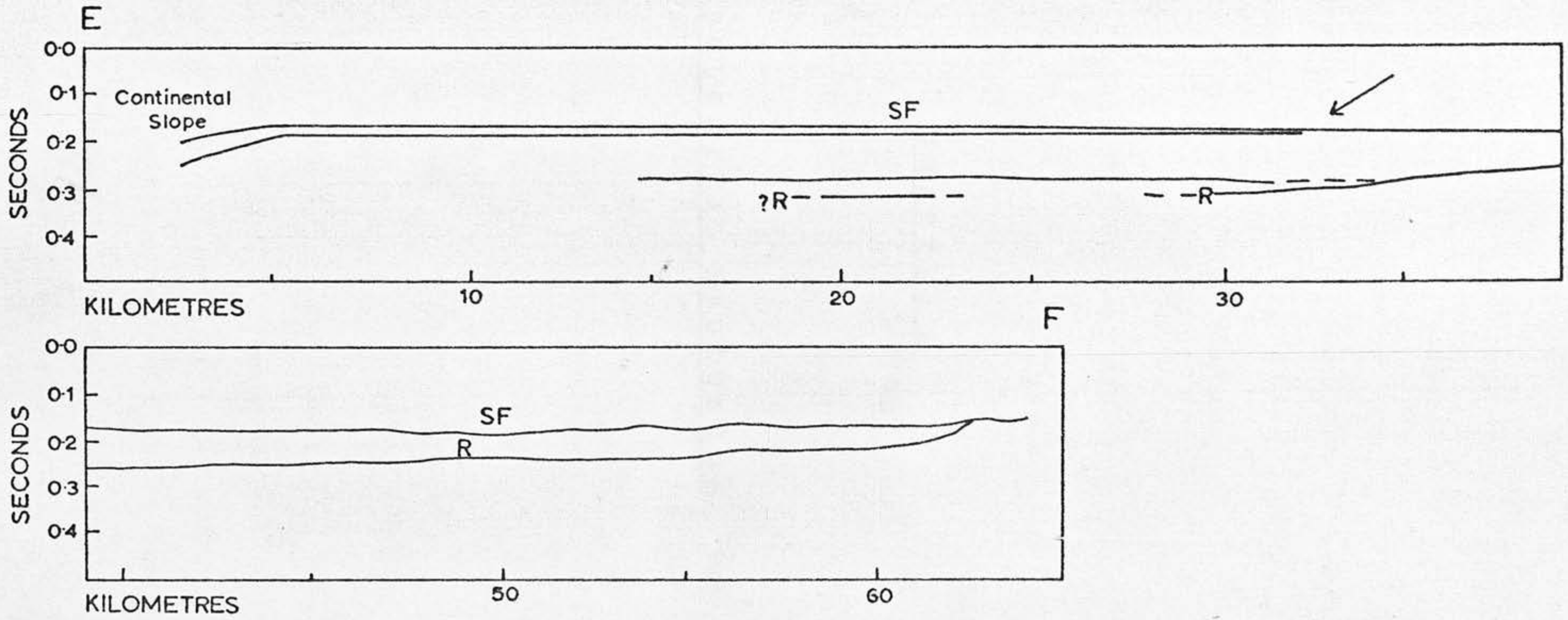



Fig.34. Section E-F, outer continental shelf. SF - Sea-floor; R - Rockhead; arrow indicates truncation of reflector by sea-floor. For location see Fig.26.

# CHAPTER 4

# GEOLOGICAL EVOLUTION

## 4.1. INTRODUCTION

In chapters 2 and 3 geophysical and geological data are interpreted and Pre-Quaternary and Quaternary geology described. In this chapter these interpretations are accepted and used, together with published onshore information, to trace the evolution of the Sea of the Hebrides from the late Palaeozoic through to the present.

## 4.2. PRE-QUATERNARY EVOLUTION

### 4.2.1. The Sea of the Hebrides - stratigraphy.

Pre-Permo-Triassic. On the trough margins the pre-Permo-Triassic surface is a major unconformity. It is therefore a convenient base for this study.

The evidence for Carboniferous sediments, at the base of the troughs is strong and the pre-Permo-Triassic surface can be expected to comprise rocks ranging in age from Lewisian to the Carboniferous. The latter, together with Devonian rocks may lie in faulted basins comparable to those seen onshore.

Permo-Triassic. Both on and offshore Permo-Triassic rocks crop out on structural highs and in the shallower sedimentary troughs. Palaeontological dating of two offshore samples(SH206 and 73/25, Appendix 2) agrees with the Triassic age assigned, on lithological and stratigraphic evidence, to the onshore deposits (Craig, 1965). A third date (SH207, Appendix 2) is Upper Permian.

The sediments include conglomerates, marls, sandstones and cornstones. Thicknesses range from ten feet to three hundred feet and "fining-upward" cycles have been described (Richey, 1961; Bruck, Dedman and Wilson, 1967). A semi-arid, alluvial fan environment is suggested by Bruck, Dedman and Wilson (1967) and by Steel (1974). Considerably greater thicknesses of New Red Sandstone have been suggested by Rast and others, (1968) - 2000m, by Smythe and others (1972) - 2000m and by Steel (in preparation) - 4000m. Where seen onshore the sediments are overlain conformably by the Jurassic.

Triassic sediments in Britain are usually considered to have been deposited in contemporaneous fault-controlled basins. The following evidence relates to the nature of the Hebridean basins:-

(i) The sedimentological evidence of Bruck, Dedman and Wilson (1967) indicates a south-westerly source (i.e. along the axis of the Inner Hebrides Trough) for the Trias of Raasay and Scalpay. Steel (1971 and personal communication) suggests alluvial fan-building across the trough was succeeded by sediment transport along the trough. This evidence suggests contemporaneous movement on the Camasunary Fault.

(ii) Steel (in preparation) similarly relates deposition of the Stornoway Formation to Permo-Triassic fault movement close to the present line of the Minch Fault.

(iii) The thin Permo-Triassic sediments on the structural high at Sligachan, Skye which pass conformably up into the Jurassic contrast with the thick sequence under north-west Skye suggested on geophysical evidence by Smythe and others. If Smythe's interpretation is correct it implies contemporary movement on both the Minch Fault and the deep north-westerly fault under northern Skye.

(iv) The structural and other evidence of Rast and others (1967) is not consistent with contemporary movement on the Great Glen Fault.

The evidence therefore is not conclusive but strongly suggests contemporary movement on the major faults during deposition of the New Red Sandstone.

<u>Jurassic</u>. Onshore Jurassic strata crop out both on the structural highs and in the Sea of the Hebrides and Inner Hebrides troughs where they reach a maximum thickness of 900m; this compares with a thickness of about 1,000m for the sediment above Horizon A in the Sea of the Hebrides Trough.

Shallow water marine sediments extend up to the Middle Bajocian (Hallam, 1965) and are succeeded by the 'Great Estuarine Series' (Upper Bajocian to Upper Bathonian) interpreted by Hudson (1962) as a brackish-water lagoonal deposit. A marine transgression in the Callovian initiates a shale sequence which continues to the top of the Kimmeridgian (Hallam, 1965).

The following evidence relates to the problem of whether the sediments were deposited in basins controlled by movements on the major north-easterly faults or whether they have been preserved by post-Jurassic movement on these faults:-

(i) Lias - There is no evidence of structually controlled basins coinciding with the present troughs in the studies of Howarth (1956) or Hallam (1959).

(ii) Bearreraig Sandstone (Bajocian) - Morton (1965) recognises two basins, one in north Skye and the other in Raasay. These are separated by "an area of relatively slow subsidence" which coincides with the present structural high separating the Sea of the Hebrides and Inner Hebrides troughs. Significant variations in thickness, however, also occur along the axis of the present trough.

(iii) Great Estuarine Series (Bajocian to Bathonian). The work of Hudson (1962 and 1964) does not recognise the influence of a structural high in the Skye area and comments on the "lateral constancy" of the sediments. Hudson (1964) however shows that sediments were derived from two sources, one coinciding with the present Scottish mainland and the other a Lewisian source to the west. The latter would be consistent with (but by no means prove) movement on the Minch Fault at this time.

(iv) Upper Jurassic. The studies of Sykes (in preparation) and Wright (1973) give no indication of fault movement.

The available evidence therefore shows that the present configuration of troughs and highs was evident only in the Middle Jurassic.

Cretaceous. The lower Cretaceous is absent and thin, marine Upper

Cretaceous sediments (Hallam, 1965) overstep onto older formations (George, 1966, Figs.2 and 3). Offshore, one sample (SH177, Appendix 2) has been assigned a Cretaceous age on lithological evidence. There is no seismic evidence however for a Jurassic - Cretaceous unconformity and so the possibility of thick structurally-controlled Cretaceous deposits in the troughs must be discounted.

Tertiary. The thin Tertiary sediments interbedded with lavas are not considered here and igneous activity is discussed with the structures. Tertiary sediments may occur in the Blackstones Bank area.

### 4.2.2. The Sea of the Hebrides - structure.

The main events in the structural history are summarised in Table 2 and sedimentological evidence for structural events is discussed above. The most important conclusion is that the main movement on the Minch and Camasunary-Skerryvore faults is post-Jurassic and pre-Tertiary lava in age. Permo-Triassic movement is suggested by sedimentological evidence. Pre-Cretaceous movement on the Camasunary Fault on Skye is strongly suggested by the presence of Upper Cretaceous sediments resting on Lias on the shore of Soay Sound, 6.5km west of the fault; pre-lava movement is confirmed by the age of the lava sub-crop on either side of the fault (Peach and others, 1910). Post-lava movement of at least 760m on the fault on Raasay is indicated by the presence of lavas lying topographically below Lewisian and Torridonian rocks across the fault. Similar movement must have occured east of Coll.

The Minch Fault truncates the major syncline of the Sea of the Hebrides - a post-Jurassic structure. Post-lava movement on the fault is indicated by the level of the lavas off Pabbay Island; these are at least 270m below mean sea level. Although post-Jurassic and pre-lava movement on the Minch Fault cannot be proved, it is not unreasonable to assume a similar history to that of the Camasunary-Skerryvore Fault.

The north-east trend of both these faults and the Great Glen Fault parallels that of the Hercynian wrench faults (Kennedy, 1946; Dearnley, 1962) and they are therefore assumed to be inherited structures. There is no evidence in this work for transcurrent movement on the faults. Both the Great Glen Fault (offshore) and the Camasunary-Skerryvore Fault lack the rectilinear character that could be cited as evidence for this. The curvilinear character of the Minch Fault as it appears on the present surface west of Skye, could be caused by differential amounts of dip during vertical movement and does not necessarily exclude the possibility of a phase of transcurrent movement. It may be significant that the centre of the arc it describes lies in the region of the Skye plutonic centre.

It is most probable therefore that these faults have had a complex history, initiated as Caledonian structures, re-activated by Hercynian stresses to give transcurrent displacement (though the present work provides no evidence of this) and finally reacting to Mesozoic and Tertiary tension with large vertical movements.

Onshore Mesozoic or Tertiary vertical movement on the Great Glen Fault may obscure the evidence for earlier transcurrent movement (cf Munro, 1973).

The evidence in this study does not affect the established sequence of Tertiary igneous activity (p.9 ) but it is relevant to the location of the Tertiary igneous ventres. Three centres, Mull, Rhum and the Black Cuillins lie on structural highs a few kilometres to the west of the major faults. The Ardnamurchan centre lies on a structural high but no north-easterly fault, transcurrent or normal, lies to the east (Geological Survey, lin. Sheet 52). The Blackstones Bank centre lies exactly midway between the Camasunary-Skerryvore and Great Glen Faults.

There is no distinct relationship between the Tertiary igneous centres and the major faults. Three of the five centres lie on basement highs to the west of the faults but these centres do not uniquely share other features (e.g. exceptionally high Bouguer gravity anomaly, north-west dyke swarms, cone sheets, ring dykes).

The suggestion has also been made that north-westerly trending faults controlled the location of the centres; - again however there is no clear relationship between the centres and north-westerly faults such as the Loch Assapol fault and the fault south-west of Stanton Banks.

### 4.2.3. Middle-Late Tertiary erosion.

George (1966, p.18) and Emeleus (1973) have discussed the evidence for the erosion which followed igneous activity. George envisages an initially rough landscape "with an altimetric range of many thousands of feet" being eroded (by mid-Tertiary times) by rivers to a "sub-mature landscape" with the "cores of igneous structure as puy-type monadnoch hills". George points out that this landscape is evidenced today by the dissected remains of three "little-warped, wave-cut benches" which "bevel the Palaeozoic igneous masses and are later than the mid-Tertiary folds and faults". "The regional landscape is essentially Neogene in origin".

The age of the dissection of these benches is uncertain. Sissons (1967) points out that many valleys are discordant to geological structure and infers that they are "direct descendants" of streams initiated "at or above the present levels of local summits". This suggests that an unknown proportion of erosion was achieved prior to the Quaternary glaciations.

### 4.2.4. Comparison with adjacent areas.

The map of Bullard and others (1965) proposing a pre-continental drift fit of the continents around the Atlantic has been used by Dewey (1969) to reconstruct the Caledonian-Appalachian orogenic belt of which the Hebridean region is a part. I accept this reconstruction in principle and the evolution of the Sea of the Hebrides is here considered in the context of a post-Caledonian opening of the North Atlantic.

The Mesozoic and early Tertiary geology of the Sea of the Hebrides has major features in common with other areas bordering the North Atlantic (Sutton, 1968).

The Rockall Plateau, shown to be a fragment of continental crust (Scrutton and Roberts, 1971) has a Tertiary Centre (Roberts, 1969; Binns and Willis, 1973; Roberts and others, 1974) set in the basement high (Roberts and others, 1973) on its eastern margin: a western basement high (the Hatton Bank) is separated from the eastern high by the Hatton-Rockall sedimentary basin. Tertiary sediments have been proved in the Hatton-Rockall Basin (Laughton and others, 1972) and if, as is possible, Mesozoic sediments underlie them then there is a strong similarity between the Rockall Plateau and the Sea of the Hebrides.

Continental red beds of Triassic age, commonly deposited in fault-controlled basins, fringe the Atlantic (Sutton, 1968). Elsewhere in Britain sedimentological evidence shows structural control of Permo-Triassic deposition in a number of basins and orientation is influenced by older tectonic trends (Audley-Charles, 1970).

The Jurassic of the Sea of the Hebrides is comparable in major features to that of the rest of Britain (Arkell, 1933, Chapter XVIII; Hallam, 1965). In East Greenland Lower Jurassic faunas from the Lower Pliensbachian stage upwards are comparable to those of the

Hebrides and lithologies in both areas indicate shallow water sedimentation. The Middle Jurassic shallow water sands and lagoonal deposits have their counterparts in the deltaic "Yellow Series" of East Greenland but faunal evidence indicates deposition in an unconnected basin. A faunal connection was resumed in the Callovian and continues throughout the rest of the Jurassic (Calloman and others, 1972).

Block faulting during the Late Jurassic or Lower Cretaceous is reported from East Greenland (Haller, 1970) and the North Sea where a major graben, initiated during this period, extends southwards from east of Shetland into Dutch Waters (Armstrong, 1972; Ziegler, 1973).

Early Tertiary igneous activity, comparable to that of Scotland, occurred in Ireland, the Faroes, East Greenland (Richey and others, 1961) as well as on the Rockall Plateau.

In East Greenland, as in the Hebrides, no clear relationship can be seen between the major faults and the plutonic centres (Haller, 1970). The Rockall centre, however, lies on a basement high to the west of the marginal escarpment of the Rockall Plateau, a position analogous to the Rhum and Black Cuillin centres.

The evolution of the Sea of the Hebrides may also be compared with that of the north-east Atlantic suggested by Laughton (1972b) on the basis of deep sea geophysical and drilling evidence. Precise correlations can not be made but the tension which caused the opening of the Rockall Trough may have caused the post-Jurassic faulting in the Sea of the Hebrides and the North Sea Graben. There is however no clear proof of this and furthermore a distinction must be made between the northerly trends of the North Sea Graben and the northern part of the Rockall Trough and the north-east trend of the western Scottish basins (see also Watts, 1971). The latter appears on the evidence of Talwani and Eldholm (1972, Fig.20) to "truncate" the North Sea graben. The north-easterly trend is parallel both to the Caledonian structure and to the Rejkanes Ridge, the Palaeocene axis of spreading (Laughton, 1972b). The northerly trend is parallel to that of the block faulting in East Greenland (Haller, 1970) in fact on the reconstruction of Bullard and others (1965) East Greenland and the Northern North Sea are structurally continuous. This suggests that the Hebrides and the North Sea-East Greenland zones both responded to Mesozoic tension by block faulting controlled by earlier structures of different trends. In the early Tertiary the north-east (Hebridian) trend dominated as evidenced by the post-lava movement on the major faults.

## 4.3. QUATERNARY EVOLUTION

### 4.3.1. Summary of stratigraphy.

The lithologies described in chapter 3 are interpreted below as being deposited diachronously by a retreating ice sheet.

The succession is:-

| | |
|---|---|
| Formation 4. | Modern sediments:- sediments deposited by, or in equilibrium with, the present marine regime. |
| Formation 3. | Periglacial-marine sediments:- sediments deposited at some distance from the ice front but composed of material eroded by glacial action. |
| Formation 2c. | Glacial-marine sediments:- sediments deposited in close association with floating ice. |
| Formation 2b. | ? Glacial-marine sediments. |
| Formation 2a. | ? Glacial-marine sediments. |
| Formation 1. | Till. |

4.3.2. Ice movement.

The high degree of lithological control of the glaciated trenches in rockhead shows that, at the latest, the presumed cover of Tertiary lavas was removed during the last glaciation.

Two hypotheses (not mutually exclusive) could account for the presence of south-westerly trenches which lie at a significant angle to the main westerly ice movements:-

(i) They were formed by distinct ice streams at a low level within the ice sheet, moving at an angle to it but powered by a component of the westerly-directed force of the ice-sheet which was diverted by south-westerly rock structures.

(ii) They were initially excavated at the start of glaciation as tongues of ice from high ground invaded the offshore area and did not float off. Once initiated these ice streams could have remained active when overrun by the main ice sheet.

I favour the second hypothesis. If diverted ice was a significant agent of erosion then the main glacial trench in the Sea of the Hebrides Trough would have been formed against and parallel to the Minch Fault southwards from Eriskay (i.e. that section of the Minch Fault which separates Mesozoic sediment from Lewisian gneiss). Erosion, however, was greatest in the trench running south-west from Rhum. The morphology of this trench clearly indicates erosion by southerly or south-westerly moving ice and there is no western scarp to divert the westerly-moving ice.

If the second hypothesis is correct it strongly implies that, as the glaciers would follow existing channels, the presumed lava cover was in large part removed before glaciation.

The point is important because the sequence would be reversed during deglaciation and the presence of glaciers from high ground becoming 'floated off' would account for the thick (Formation 2) glacial-marine sediments which fill the trench.

4.3.3. Till.

Formation 1 sediments are interpreted, on the basis of lithology or surface morphology, as till. The seismic and borehole evidence suggests, surprisingly, that little till was deposited offshore. A possible explanation is found in Carey and Ahmad (1961, p.885). They point out that if the temperature of the base of a glacier is above freezing point ('wet-based' glaciers) till is deposited inland.

4.3.4. Glacial marine sedimentation.

Formation 2c has been interpreted as glacial marine sediment. The presence of gravel grade (>2mm) material in a fine grained (>63$\mu$) matrix has been held to indicate deposition of glacial sediment into a marine environment and attempts have been made to explain variation in lithology (e.g. Carey and Ahmad, 1961; Lavrushin, 1968). This, together with stratigraphical position beneath late-glacial sediment of Formation 3 and distribution on the courses of the main ice streams suggests Formation 2 was deposited in close association with ice. However, in spite of the firmness of the sediment and the presence of gravel grade material, the consistently distinctive marine dinoflagellate cyst assemblage and the stratification seen on seismic profiles indicate that this formation comprises marine sediment not till.

The nature of this sediment further invites comparison with the 'wet-base glacier' environment described by Carey and Ahmad

(1961, p.885). Another point of similarity is the "till" in borehole 72/12 which could be a sub-marine flow-till.

A comparison of the environments of deposition of Formations 2 and 3 is given in section 4.3.5.

Sediments of Formation 2 make an important contribution to the thickness of Quaternary sediment. The great variations in their thickness cannot be proved to be depositional in origin but my interpretation assumes that they are.

On the inner shelf 160m of Formation 2 in the trench north-west of Coll contrasts with its absence further west (Fig. 31): the considerable thickness of Formation 2 in the Blackstones Bank area contrasts with its absence in the Firth of Lorne. In both cases sediment could have been removed by tidal or other currents. However Formation 2 is very firm and has resisted erosion both by currents and swell in the area of Borehole 72/12.

There is some evidence for erosion on the outer shelf (Fig.34): this may be attributed to iceberg ploughing (Belderson and others, 1973) or to the tidal or other currents of a new post-glacial marine regime.

It is suggested therefore that the variations in thickness of Formation 2 are depositional in origin and can most easily be related to the presence of major ice streams: the outer shelf sediments were deposited by tha main ice sheet and those north-west of Coll by major, south-westerly moving ice streams at a more advanced stage in the retreat. Their thickness reflects the size and activity of their parent ice-sheet or glacier. The absence of sediment in the Firth of Lorne, the channel along which the sediment west of Colonsay was transported, could be explained by a rapid floating off of the ice at this point in its retreat.

No explanation can be given for the firmness of the sediment.

## 4.3.5. Peri-glacial marine sedimentation.

Formation 3 is interpreted as "peri-glacial" marine sediment by analogy with the sediments currently being deposited off Southern Alaska (Wright and Sharma, 1969). Here poorly-sorted (cf Morgan and others, 1973 and Wright and Sharma, 1969 Fig.2) muddy sediments from an ice-front onshore are being deposited at rates of 250m/1000yrs. Assuming deposition in borehole 71/9 (p.77) was continuous the radio carbon date indicates that the older "warm-water" fauna belongs to the Allerød interstadial, the "cold-water" fauna to the period of the Loch Lomond valley-glacier, readvance and the younger warm-water fauna to the final climatic amelioration.

During deposition of this sequence therefore, ice, when present, lay behind or very close to the present coastline (Sissons, 1967, p.137). A plentiful supply of sediment could be expected both from marine erosion of loose morainic debris on the sea floor and coastline and from fluvio-glacial sources; this would account for the high sedimentation rates.

The poor recovery of dinoflagellate cysts in borehole 71/9 between 26m and 16m is attributed to a continuously high level of suspended matter (produced by the Loch Lomond readvance) and not to low water temperature. The significant populations of Formation 2 are inferred to have lived in clear, cold water adjacent to floating ice. Potential suspended matter remained frozen into the ice to be released intermittently, perhaps by seasonal melting, to form Formation 2 deposits.

Formation 3 never achieves the same thickness as Formation 2. The influence of its variations in thickness (which mostly occur around the Inner Hebrides) on the morphology of the present sea-floor is therefore much less. These variations can be related to current action although whether they are original depositional features cannot be proved with existing data. The evidence of Fig.31 suggests that they are original. On section A-B the bedding is not truncated by the depression to the south-east of the shoal at B. Sedimentation here is clearly slower and I have interpreted this as a "moat" effect. Increase in current velocity as water is diverted round the shoal slows deposition; - however a supply of coarser material derived from the shoal is in equilibrium with the faster regime and its deposition (in beds dipping off the shoal) displaces the moat to the south-east. The bathymetric depression (Fig.3) thus owes only its linearity and possibly its southern closure to the underlying glacial morphology; its northern closure coincides with the end of the shoal.

Formation 3 sediments are softer than those of Formation 2 and may be expected to be less resistant to erosion: further they have been deposited at a time when the present marine regime operated. These factors explain the insignificant Formation 3 thickness in the Firth of Lorne - Sound of Mull channel, where there are strong tidal currents, and the contrast (cf boreholes 71/9 and 72/12, Fig.27) between the areas east and west of Colonsay. In the area protected from the prevailing swell east of Colonsay 30m of sediment lie at a topographically higher level than the surface of Formation 2 to the west.

#### 4.3.6. Modern sedimentation.

Shallow core samples (Figs. 28-30) show that modern sediments are thin and therefore do not significantly affect sea-floor morphology. They form a separate study and are not considered here.

#### 4.3.7. Synthesis.

If my interpretation of the origin of each formation is correct then the succession was most likely to have been deposited diachronously by the retreating ice of the last (Devensian) ice-sheet.

The Formation 2 sediments on the outer continental shelf (Fig.26) were deposited by the main ice-sheet, and those west of Colonsay and north-west of Coll (Figs. 26 and 31) by major, south-westerly-moving ice streams, probably at a more advanced stage in the retreat. Their thickness reflects the size and activity of their parent glaciers. Formation 3 sediments were deposited at a distance from the ice. When the supply of Formation 3 sediment became exhausted and sea level readjusted to its present position the deposits of Formation 4 were formed.

This is an initial hypothesis consistent with the facts that we have. The size of the problem is such that it will undoubtedly prove an oversimplification.

It is clear, however, that the morphology of the present sea floor is a function firstly of the morphology of rockhead (itself dependant on Pre-Quaternary geology), secondly on depositional processes during the retreat of the ice-sheet and thirdly of differential erosion of glacial sediment by the present marine regime.

4.3.8. Comparison with other areas.

The bathymetry of the area is typical of a glaciated continental shelf (Guilcher, 1966). Little seismic information is yet available from other glaciated shelves and a comparison has not been made. Such data as are available from the U.K. continental shelf are not inconsistent with my interpretation.

Deegan and others (1973) recognise in the Clyde similar sediments to my Formations 1 and 3 and, not surprisingly in these more sheltered waters, a thicker equivalent of Formation 4.

In the North Sea a similar seismic stratigraphy has been noted (Binns and others, 1974c) and comparable lithologies have been recovered in shallow boreholes (R.Holmes and D.Lawson, personal communication). Work however is in an early stage. A notable difference is the presence of deep narrow channels cutting into both glacial and pre-Quaternary rocks (Thomson, in preparation; Dingle, 1971).

Garrard and Dobson (1974) make no reference to glacial-marine sediment in the Irish Sea but their "Irish Sea Till"... "recorded, on continuous seismic profiles, as a single acoustically homogeneous unit" and lying above lodgement till compares with my Formation 2.

# C H A P T E R 5

# P O S T S C R I P T

Since 1968 a considerable volume of new data has been collected in the Sea of the Hebrides and an interpretation of the geology based on it has been made in this study. It is important to set this interpretation in a historical perspective. The variety and complexity of both the structure and stratigraphy is such that new seismic or sample data inevitably alter or modify the map. A recently released commercial deep seismic section for example has provided strong evidence for a small basin of Tertiary sediments lying on downwarped lava north of Canna (Kenolty and Smythe, in preparation: "area of uncharacteristically steep dips", Fig.5). Areas such as the southern part of the Sea of the Hebrides Trough and the area south of Mull are poorly understood and many domains have yet to be sampled. The study of glacial-marine sediments is new and the main Quaternary sections north-west of Coll and Tiree and on the Outer Continental Shelf have yet to be cored.

Allowing for the advance in the science itself therefore I feel our present state of knowledge may be compared with that of the onshore areas in the nineteenth century and one must avoid believing, as did Nicol (1844) in introducing a map and description of Scottish geology, that "little absolutely new can be expected".

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Mr. C. Chaplin and Mr. R. Devine photographed the seismic records.

Figures 2, 4, 10-13 and 28-30 are reproduced with the permission of the Director, IGS. Figs. 27 and 31 are reproduced with the permission of the Editor, Nature.

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# APPENDIX 1

## SURVEYS

| SURVEY NUMBER | SHIP AND DATE | PROJECT | REFERENCE TO CRUISE DETAILS |
|---|---|---|---|
| 68/5 | R.R.S.John Murray 20.9.68. to 3.11.68. | Geophysics. Rock and sediment sampling. | Binns, P.E., McQuillin, R. and Kenolty, N., 1974. The geology of the Sea of the Hebrides. Rep.No.73/14, Inst.geol.Sci. |
| - | M.V.Maria W. 25.7.69. to 27.8.69. | Rock and sediment sampling. | |
| - | M.V.Vickers Venturer and Pisces. 1.6.70. to 10.6.70. | Rock and sediment sampling. Observation. | |
| 70/5 | M.V.Surveyor 4.9.70. to 14.10.70. | Geophysics. | |
| 70/8 | M.V.Vickers Venturer 4.9.70. to 27.9.70. | Geophysics. Rock and sediment sampling. | |
| - | M.V.Whitethorn 9.3.71. to 1.4.71. | Over-the-side drilling. Sediment sampling. | |
| 71/S2 | M.V.Surveyor 21.8.71. to 17.9.71. | Rock and sediment sampling. | |
| 72/W2 | M.V.Whitethorn 7.4.72. to 8.5.72. | Over-the-side drilling. Sediment sampling. | Thomson, M.E. and others, In preparation. IGS marine drilling with M.V.Whitethorn in Scottish waters, 1972-73. Rep.Inst.geo.Sci. |
| 72/5 and 6 | M.V.Researcher | Geophysics. | Bacon, M., Cruise report: Project 72/5:IGS Marine Geophysics Unit Report 35. |
| 73/WH13 | M.V.Whitethorn | Over-the-side drilling. Pinger profiling. | |

# APPENDIX 2

## PRE-QUATERNARY ROCK SAMPLES

Full details of the samples tabulated below are given in the following references:


1. Binns, P.E., McQuillin, R. and Kenolty, N., 1974. The geology of the Sea of the Hebrides Rep. No. 73/14. Inst. geol. Sci.
2. Thomson, M.E. and others. In preparation. IGS marine drilling with m.v. Whitethorn in Scottish waters 1972-73. Rep. Inst. geol. Sci.
3. Warrington, G., 1972. IGS Palaeontology Department Report 72/99.
4. Warrington, G., 1972. IGS Palaeontology Department Report 72/83.
5. Elliot, R.W., 1974. IGS Petrography Department Report. 8.2.74.
6. Warrington, G., 1973. IGS Palaeontology Department Report 73/271.
7. Warrington, G., 1973. IGS Palaeontology Department Report 73/250.


| IGS REGISTERED NUMBER | LOCATION | DESCRIPTION | REFERENCE WITH FULL DETAILS |
|---|---|---|---|
| SH28 | Lat. 56°52'N Long.06°05'W | Olivine basalt (Tertiary) | 1 |
| SH119 | Lat. 57°18'N Long.06°35'W | Olivine basalt (Tertiary) | 1 |
| SH133* | Lat. 56°20'N Long.07°21'W | Shale (Jurassic - Lower Cretaceous) | 1 |
| SH166* | Lat. 56°47'N Long.06°03'W | Calcareous sandstone (Jurassic) | 1 |
| SH175* | Lat. 57°00'N Long.07°11'W | Decomposed tuff | 1 |
| SH177* | Lat. 56°55'N Long.07°18'W | White sandstone (? Upper Cretaceous) | 1 |
| SH206* | Lat. 57°25'N Long.07°08'W | White sandy limestone (Rhaetic-Hettangian) | 1 |

* Gravity corer sample

| | | | |
|---|---|---|---|
| SH207* | Lat. 57°25'N<br>Long.07°08'W | Red mudstone<br>(Late Permian) | 1 |
| SH216 | Lat. 56°15'N<br>Long.07°56'W | Microcline granite<br>(Lewisian) | 1 |
| SH217 | Lat. 56°16'N<br>Long.07°55'W | Microcline granite<br>(Lewisian) | 1 |
| SH221 | Lat. 57°01'N<br>Long.06°35'W | Olivine basalt | 1 |
| SH223 | Lat. 57°01'N<br>Long.05°53'W | Dolerite<br>(Tertiary) | 1 |
| SH226 | Lat. 56°44'N<br>Long.06°25'W | Red arkose<br>(Torridonian) | 1 |
| SH237 | Lat. 56°06'N<br>Long.06°04'W | Basalt<br>(Tertiary) | 1 |
| SH579 | Lat. 56°05'N<br>Long.07°10'W | Gabbro<br>(Tertiary) | 1 |
| SH725 | Lat. 56°21'N<br>Long.07°04'W | Diopside-scapolite rock<br>(Lewisian) | 1 |
| SH727 | Lat. 56°25'N<br>Long.06°50'W | Hornblende-pyroxene granulite<br>(Lewisian) | 1 |
| SH767 | Lat. 56°43'N<br>Long.06°47'W | Red arkose<br>(Torridonian) | 1 |
| SH768 | Lat. 56°43'N<br>Long.06°47'W | Red arkose<br>(Torridonian) | 1 |

* Gravity corer sample

| | | | |
|---|---|---|---|
| SH776 | Lat. 56°04'N<br>Long.07°08'W | Eucrite<br>(Tertiary) | 1 |
| 71/9 | Lat. 56°04'N<br>Long.06°06'W | Red sandstone<br>(Barren) | 1 |
| 71/10 | Lat. 57°01'N<br>Long.06°05'W | Dark grey sandstone<br>(Jurassic-Lower Cretaceous) | 1 |
| 72/6 | Lat. 56°54'N<br>Long.06°02'W | Dark grey, calareous sandstone<br>(Barren) | 2 & 3 |
| 72/9 | Lat. 56°23'N<br>Long.06°20'W | Psammitic schist<br>(Moine) | 2 |
| 72/10 | Lat. 57°24'N<br>Long.07°08'W | Red-brown mudstone with calcite veins.<br>(Barren - ? Permo-Triassic) | 2 & 4 |
| 72/11 | Lat. 56°42'N<br>Long.07°55'W | Red arkose<br>(Torridonian) | 2 |
| 72/12 | Lat. 56°14'N<br>Long.06°53'W | Olivine dolerite<br>(Tertiary) | 2 & 5 |
| 73/25 | Lat. 56°08'N<br>Long.06°01'W | Red Sandstone<br>(Triassic) | 2 & 6 |
| 73/27 | Lat. 56°16'N<br>Long.06°13'W | Greenish sandstone<br>(Barren) | 2 & 7 |

APPENDIX 3

PUBLICATIONS

NATURAL ENVIRONMENT RESEARCH COUNCIL

INSTITUTE OF GEOLOGICAL SCIENCES

Report No. 71/16

# Geological investigations with a manned submersible off the west coast of Scotland 1969-1970

R.A.Eden, B.Sc., F.R.S.E., D.A.Ardus, B.Sc., P.E.Binns, B.Sc., R.McQuillin, M.Sc. and J.B.Wilson, B.Sc., Ph.D.

London: Her Majesty's Stationery Office 1971

THE INSTITUTE OF GEOLOGICAL SCIENCES

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SBN 11 880211 9



*Reference to this report*

It is recommended that reference to this work be made in the following form:
Eden, R.A. and others, 1971. Geological investigations with a manned submersible off the west coast of Scotland 1969-1970. *Rep. No.* 71/16, *Inst. geol. Sci.* 49 pp.

## PREFACE

This report brings together the geological data from two cruises in the course of which IGS staff took part in 24 dives with the Vickers submersible Pisces. The first cruise was from the 7th to 12th November 1969 when the submersible was on charter to the Research Vessel Unit of the Natural Environment Research Council for evaluation purposes. Operations were in Lower Loch Fyne where Messrs Eden and Ardus took part in four dives in which geological work was possible, although during some of these, observations were also being carried out by workers in other disciplines.

At the time of the Loch Fyne work no external tools were available on the submersible except for a torpedo recovery claw. The results of the trial were, however, regarded as sufficiently encouraging to justify a full scale Institute of Geological Sciences investigation, from 8th to 17th June 1970, when twenty dives were made at selected localities in the Sea of the Hebrides as part of a reconnaissance study of the geomorphology, sediments and solid geology of the area.

During the 1970 cruise, work underwater was shared equally between Mr. R.A. Eden, Mr. D.A. Ardus and Mr. P.E. Binns, the last-named being responsible for most of the dive planning. In addition the following observers were carried for training purposes, to contribute to special aspects of the work or to assist them in their own studies: Professor G.Y. Craig of Edinburgh University, Dr. A. McLean and Dr. G. Holland of Glasgow and Durham Universities respectively, Mr. N.G.T. Fannin, Mr. C.E. Deegan, Mr. R. Floyd, Mr. H. Robertson and Mr. J. Butler of IGS, and the Director of IGS. Mr. R. McQuillin of IGS Marine Geophysics Unit took part in the underwater work, but his contribution to the present report has largely taken the form of providing the geophysical data used to control the study; Dr. J.B. Wilson of the National Institute of Oceanography also took part in the underwater work and has contributed Appendix 2; Mr. H. Robertson was the cruise photographer.

For the 1970 investigation the submersible was better provided with scientific equipment, partly by Messrs Vickers and partly from IGS and Research Vessel Unit sources. In addition the assistance of the Aberdeen Marine Laboratory, by the loan of film cameras, is acknowledged with thanks. Nevertheless, the provision of comparatively simple tools and equipment for this advanced vehicle has not yet caught up with the requirements of underwater geological work and further developments are being initiated as a result of experience gained during the second charter.

The Hydrographer to the Navy is thanked for his permission to incorporate recent unpublished data from Hydrographic Department surveys in some of the figures. The interpretations of this data shown on the figures are, however, solely the responsibility of the authors.

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1st October 1971

CONTENTS

ILLUSTRATIONS

## SUMMARY

An account is given of twenty-four dives with the submersible Vickers Pisces. Most of the dives were on glaciated trenches and associated rocky shoals inshore and around the Inner Hebrides, but three were in the central trough of the Sea of the Hebrides, two on isolated rocky and stony banks well out to sea and two at the top of the continental slope.

The sea floor is heavily glaciated. Smoothed and plucked masses of hard rock project as shoals or form cliffs bounding U-shaped trenches, and morainic debris is widespread. There has been reworking of lithic detritus in the west, with the formation of spreads of cobbles at the top of the continental slope, around the outlying banks and in gullies closer inshore. Modern mobile sand or shell sand overlies the cobble layer. The cobble beds at the top of the continental slope pass downwards to sand with scattered cobbles and isolated boulders. Mud is being deposited in deep trenches and in shallower waters inshore, where it is mixed with shell sand.

Pisces is assessed as most useful for detailed observation and sampling of critical or type localities, particularly for investigation of the interrelationship of sediment facies and local geomorphology.

## SOMMAIRE

Ce rapport rend compte de 24 plongées avec le submersible Vickers Pisces. La plupart des plongées avait lieu sur des fossés érodés par des glaciers et sur des hauts-fonds rocheux associés près de la côte et autour des Inner Hébrides, mais trois plongées étaient effectuées dans le fossé central de la Mer des Hébrides, deux sur des bancs isolés rocheux et pierreux bien loin de la côte, et deux au sommet de la pente continentale.

Le fond de la mer est fort érodé par des glaciers. Des masses unies ou rugueuses de roches dures en sortent, comme des hauts-fonds, ou forment des falaises aux bords des fossés en U, et des débris morainiques sont répandus. Le détritus lithique a été remanié à l'ouest, avec la dispersion de galets au sommet de la pente continentale, autour des bancs éloignés et dans des couloirs moins éloignés de la côte. Du sable récent, ou du sable coquillier, couvre la couche de galets. Les assises de galets au sommet de la pente continentale passent, en descendant, au sable avec des galets dispersés et des blocs isolés. Des dépôts de boue se forment dans les tranchées profondes et dans les eaux moins profondes près de la côte, où ils sont mélangés avec le sable coquillier.

On reconnaît que Pisces est très utile pour des observations détaillés et la prise d'échantillons aux endroits critiques ou typiques, surtout pour la recherche dans le rapport entre les faciès sédimentaires et la géomorphologie locale.

## ZUSAMMENFASSUNG

Man berichtet über 24 Untertauchen mit dem Tauchfähigapparat Vickers Pisces. Die meisten Tauchen waren auf vereisten Rinnen und auf begleitenden felsigen Untiefen in der Nähe der Küste und der Inneren Hebrides: drei aber waren im Mittleren Trog vom Meer der Hebriden, zwei auf isolierten felsigen Bänken weit von der Küste und zwei auf dem Gipfel des Kontinentalabfalles.

Der Seeboden ist stark vereist. Geglättete oder gerauhte Massen von harten Felsen strecken als Untiefen vor oder bilden Klippen, die U-geformte Rinnen begrenzen. Moräne-Schutt ist weitverbreitet. Es gab Aufarbeiten von lithischem Gesteinsschutt im Westen mit der Formation von Ausbreitung von Kieselsteinen auf dem Gipfel des Kontinentalabfalles, um die entfernten Bänke herum und in Rinnen, die der Küste näher sind. Moderner beweglicher Sand oder Muschelsand überlagert die Kieselsteinschicht. Die Kieselsteinschichte auf dem Gipfel des Kontinentalabhanges gehen zum Sand mit zerstreuten Kieselsteinen und isolierte Blöcke hinunter. Kot wird

in tiefen Rinnen und in seichteren Wassern in der Nähe der Küste abgelagert, wo es mit Muschelsand gemischt wird.

Man bewertet Pisces als am nützlichsten für die ausführliche Untersuchung und Bemusterung von kritischen oder typischen Lagen, besonders für die Untersuchung der Wechselbeziehung von Sediment-fazies und örtliche Geomorphologie.

# Geological investigations with a manned submersible off the west coast of Scotland, 1969-1970

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## INTRODUCTION

The account which follows details geological work carried out and results obtained in two cruises with the Vickers Submersible Pisces and her mother ship R. V. Vickers Venturer from 7th to 12th November 1969 in Lower Loch Fyne (Natural Environment Research Council, 1970), and from 8th to 17th June 1970 in the area of the Sea of the Hebrides (Fig. 1). The programme during the second period was based mainly on problems arising from IGS geophysical traversing in 1968 with R. R. S. John Murray and sampling in 1969 with M. V. Maria W; these earlier projects are reported separately (McQuillin and others, in preparation). The work forms part of the IGS survey of the UK continental shelf.

In the course of the twenty-four dives with Pisces a total of 147 man hours has been spent on the sea floor by IGS and invited personnel. Staff involved, site locations and weather conditions are listed in Appendix 1. All depths in the account are in metres below Mean Sea Level. All echo sounder traverses shown on the figures have been adjusted to a uniform horizontal scale.

## GEOLOGICAL OBJECTIVES AND CONCLUSIONS

The IGS surface reconnaissance surveys made in 1968 and 1969 showed that, like the adjoining islands and mainland, the sea floor off the west coast of Scotland is an area of complex geology and relief. Most of the formations which have been the subject of classic studies on land (Richey and others, 1961; Craig, 1965) are exposed on the sea floor which has the characteristic topography of a glaciated shelf (Guilcher, 1966). Overdeepened trenches divide the islands and shoals of the Inner Hebrides and a broad longitudinal depression marks the line of the complex Minch Fault (McQuillin and others, in preparation). In the south, Stanton Banks and the Blackstones Bank are rocky shoals rising from an otherwise flat sea floor which extends westward to the continental slope.

The geological objectives of each dive are discussed later in this account but the overall intention of the work was to assist IGS surface reconnaissance surveys by providing an opportunity for close examination of the representative geomorphological features and sedimentary environments and the transitions which take place between them. In addition it was hoped to sample rock outcrops at some locations. Both the 1969 and 1970 programmes were regarded as part of an extended evaluation of the use of a submersible for this type of work.

The results of this study will be incorporated with other data before firm conclusions are drawn but some observations may be made at this stage:

1. The work emphasises the dominance, already evident from a study of Admiralty charts (Sissons, 1967), of glacial action in moulding the sea floor. On many of the dives the submersible climbed from a flat, sediment filled trough up the steep rock walls of a U-shaped valley. All the shoals crossed have typical glacially smoothe or plucked rock surfaces. Striae were only observed on two occasions, possibly due to the abundant cover of epifauna.

2. The deep troughs, even those near shore, are floored chiefly by fine-grained sediments with a bioturbated layer at the top (Plate 8b). The action of burrowers in this layer is helping to keep manganese nodules near the sediment surface in Lower Loch Fyne. Coarser grained sediments usually occur towards the margins of deep hollows.

3. The sediments on the shoals vary considerably. Around Skye and the Small Isles the sediments in the hollows and gullies of the shoals are poorly sorted and contain variable amounts of lithic and shell material; a much higher percentage of fines is present than is the case further offshore, and ledges on the rock faces support thin films of mud. In marked contrast Stanton Banks are almost completely free of fines and the sediment is

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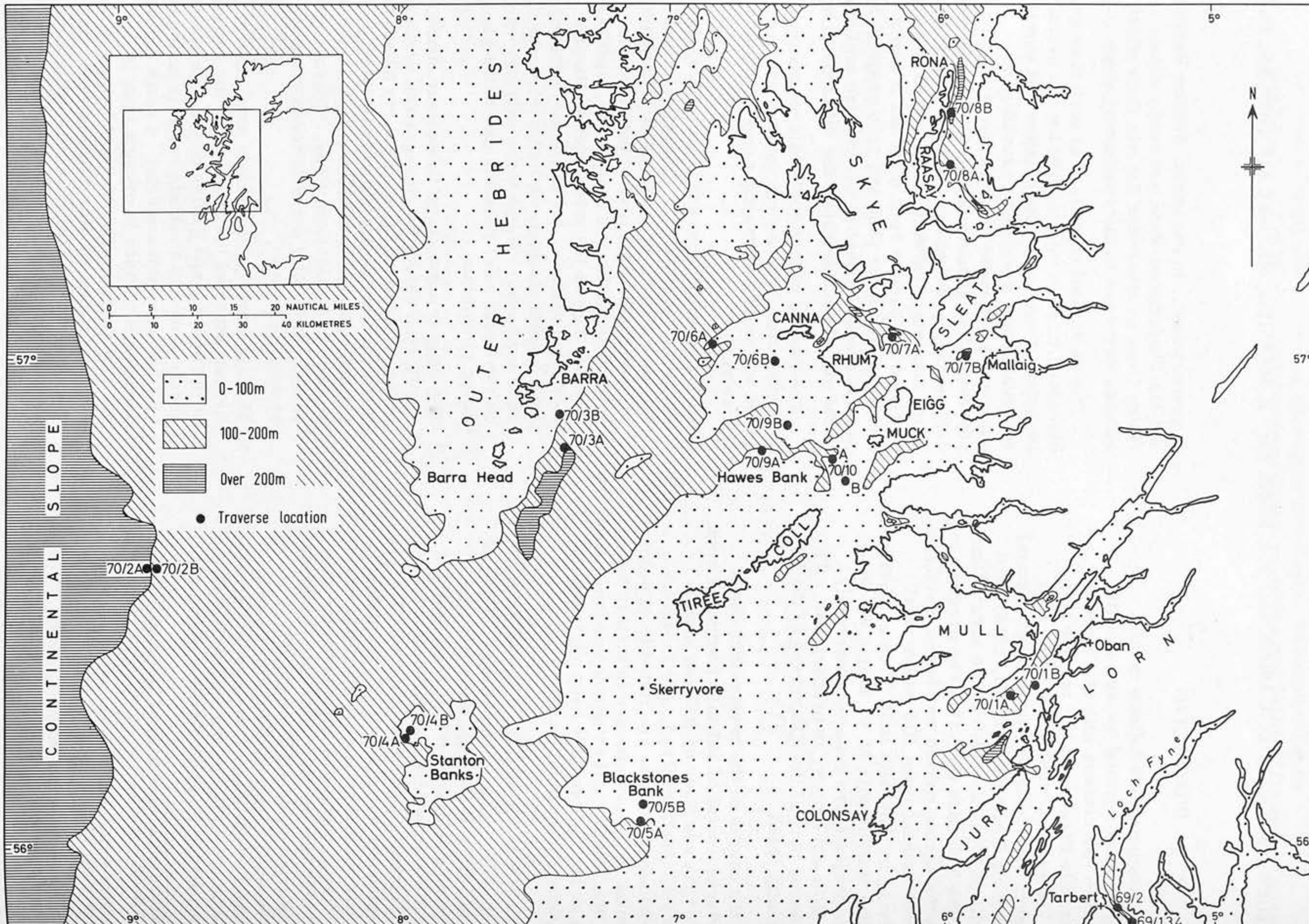



Fig. 1. General plan showing locations of traverses with Pisces.

coarse, well-sorted shell sand.

4. Current-rippled coarse sands are common in the gully sediments on shoals. Most are orientated at right angles to the gully walls and are probably formed by shoaling currents becoming funnelled through the gullies.

5. The evidence is consistent with the existence of a former low sea level, lower in the west than in the east. Freshened up rock surfaces swept free of glacial detritus, cliffs with angular boulder scree at their bases, gullies and fissures, and spreads of rounded cobble gravel, all occur at lower levels in the west than in the east, where unmodified glaciated surfaces encumbered by morainic detritus extend up into shallow water.

6. Sediments on the upper continental slope are predominantly sandy but towards the top of the slope, spreads of rounded cobbles become common and the presence of boulders up to a metre across suggests that this coarser material at least has been transported by glacial agencies. This being the case it follows that little net recent sedimentation has taken place, but there are indications of northward migration of sand along the contour.

## SUBMERSIBLE VICKERS PISCES AND R.V. VICKERS VENTURER

Specifications of Pisces and her mother ship R.V. Vickers Venturer (Plate 1), are summarised in Appendix 3. Initial British trials of Pisces took place early in 1969, and the first commerical charter of the submersible with its mother ship was that for NERC in November 1969.

The submersible, which is free diving, is able to carry a pilot and two observers, together with a limited amount of scientific equipment. It is designed for work to a maximum depth of 1060 m (3500 ft), but its deepest dive to date has been to 740 m during trials in Canada. Accommodation is cramped but not unduly uncomfortable for limited periods. The crew and control panels are housed inside a steel sphere, two metres in diameter, containing air at atmospheric pressure; this cabin is provided with three observation portholes in its lower part, and two couches plus a bench seat. Machinery, oil and air containers are carried outside the main sphere, and the whole is enclosed in a fibre-glass outer shell mounted on skids; access is by a conning tower. Propulsion is provided by two battery powered, reversible electric motors driving propellors which give a maximum speed of about two knots. There are a number of built-in safety facilities including an ability to make rapid ascents, to drop ballast and to jettison some of the external parts should they become entangled. No lengthy operational training is necessary for observers.

Instrumentation carried during the present work included methods of depth indication, sonar voice communication with the mother ship, sector scanning sonar, a gyro compass, and an internal T. V. camera which can be manually directed through any of the portholes. There are two external floodlights, each of 1000 watts.

The longest mission carried out to date lasted twelve and a half hours, but IGS practice has been to make two dives per day, each ideally of about four hours on the sea floor, with a change of personnel and equipment check between dives.

The mother ship, R. V. Vickers Venturer, is a converted trawler, a sister ship of the NERC vessel R. R. S. John Murray. Conversion has included incorporation of a deep cut-out platform in the stern to provide a sheltered docking area for the submersible a metre above water level (Plate 1a). For launching, the submersible is lifted by a hydraulic A-frame (Plate 1b), its attitude when suspended being controlled by a tow line and two steadying lines on each side. The six lines are detached by a diver once the submersible is in the water, and for recovery they are similarly re-attached. Launch and recovery are carried out with the mother ship under way slow ahead, so that the submersible streams behind in a controlled attitude; it was towed bow-first in 1969 and stern-first in 1970, the latter method reducing the degree of yaw. Recovery has been successfully made in winds up to Force 8 and waves up to 4. 5 m, so weather conditions do not impose serious problems in British waters in normal summer months; one of the limiting factors is, however, the ability of the diver to operate in poor weather.

The Pisces team aboard R. V. Vickers Venturer normally consisted of a party leader and four pilots, all being also divers and specialists in trades appropriate for servicing the vessel.

### Location Methods

An accurate location system is necessary for geological work. On the two cruises, the only method available has been dead reckoning between the launch and recovery points, which were fixed from the mother ship by Decca Navigator, and radar or sighting when possible. During each dive a check was kept on time, heading, speed and depth, so that it was subsequently possible to reconstruct the course followed and to pinpoint features with a fair degree of accuracy. Sonar location systems working both from the submersible and from the mother ship are under evaluation.

## Methods and Equipment for Geological Work

The system of submersible plus mother ship having been developed to a stage at which operations have become routine, the next phase is the design of adequate tools for the system; this is now in hand. Many of the requirements for geological work are simple and inexpensive, others are complex, but most of them require time and experience to become fully operational.

Without external handling tools the submersible is capable of observation only, and this has in fact been found to be its main value for geological work. It is, however, feasible to design tools (Winget, 1969) to obtain solid rock and sediment samples from a submersible at the same time as observations are being made, and several such tools were employed during the 1970 work, with varying degrees of success. Fewer samples were obtained than had been wished, and because of this it was not possible to identify the rock type at some exposures.

### *Torpedo Claw*

A massive claw shaped to fit round torpedoes is the basic tool of Pisces. It has only limited power of manoeuvre, but can be clamped to selected large rock fragments or boulders to bring these to the surface. It can dig into sediment to permit observation of what lies below the surface, and it can carry equipment to be placed on, or pressed into, the sea floor.

### *Harrison Rock Drill*

An IGS Harrison rock drill (Eden, Flinn and Harrison, 1970), modified by removal of its frame, switching and withdrawal mechanisms, was bolted to the torpedo claw and successfully used for underwater coring (Plate 2b). The drill, which weighs 15 kg and has a 250-mm core barrel with an internal diameter of 6.4 mm, is powered by two six-volt batteries; its normal photocell switch was replaced by a solenoid switch operated from within the submersible. Although successful, the drill requires redesign before becoming a routine tool for the submersible, because its power-needs cannot be supplied by the batteries of Pisces and because the drill bit describes an arc of a circle as it is lowered by the vertically pivoting arm of the claw, so that only limited penetration is possible before there is a risk of the bit becoming jammed. Because of this risk it was arranged that the drill could if necessary be jettisoned, and experimental drilling was confined to Scuba diver depths, the submersible towing a marker buoy.

### *Handling Arm*

Pisces carried a versatile telechiric arm during the second period of IGS use. This was able to pick out small, selected rock fragments and put them into an external basket. Even on glaciated pavements it was usually possible to obtain in situ material in this way, providing that the rock was adequately jointed or fractured. The arm was put out of action by collision with a rock during the cruise and additional protection and a comprehensive spares kit are required to keep this useful arm operational in rocky areas.

### *Geological Rack and Tools*

An external geological rack was fitted to carry equipment to be used by the handling arm. This included a rock basket, chisels and levering devices with suitable grips for the handling arm, and four sediment corers (Plate 2a) similar to those designed for use with the Woods Hole submersible 'Alvin' (Winget, 1969). The corers are polythene tubes about 300 mm long with non-return valves at the top to help retain samples. Each tube is pushed into the sea floor by the handling arm by means of a metal handle at its top. After the sample has been obtained the tube is returned to its seating on a rubber bung which prevents loss of sediment at the air/water interface when Pisces is recovered. Cores of mud and silt were successfully collected in this way, but the suction of the non-return valve was inadequate to retain sand samples, and a closable scoop is required for such material.

### *Closed Circuit Television*

During the second cruise, about thirteen hours of Sony video tape record was obtained with the internal T.V. camera provided; this was copied on IGS Ampex tapes aboard R.V. Vickers Venturer and reduced to about four hours of running time, providing a good quality visual record of the areas examined. It would be an improvement if a camera could be mounted low down externally in such a position that its attitude could be controlled by the handling arm. This would provide close up views of the sea floor and release additional space within the cabin.

### *Photographic Cameras*

During the first IGS cruise with Pisces, photographs were taken through the 3-in thick perspex portholes using available light from the submersible's two 1000-watt quartz-iodine lamps. With Tri-X film in a Hasselblad EL camera it usually proved necessary to give 1/30 sec at f 2.8 to obtain an adequate exposure; most of the negatives show poor contrast, low resolution and restricted depth of field. Because of this a 35 mm UMEL flash camera belonging to RVU was mounted externally during the second cruise; control was from within the cabin. Despite initial mechanical difficulties good quality photographs were obtained using Tri-X film, 1/60 sec at f 11.

*Working Methods*

It was found that several training dives were necessary before an observer could take full advantage of the opportunities provided by the submersible. An effort was made to keep the fullest record by video tape, photographs and tape-recorded descriptions, so that each dive could later be reconsidered. The duties of the observer included reporting immediately after recovery of Pisces when observations were collated and initial conclusions written down. Three main observers, of whom one was present on each dive, constituted a minimum team.

Because the maximum speed of Pisces is 2 knots it was preferable to work with the current. In planning the traverses, therefore, a compromise had to be reached between the current direction and the most suitable course from the geological point of view. Before each dive at least one echo sounder profile was obtained; at some locations three parallel traverses were made, partly to aid positioning where detailed Admiralty surveys were not available and partly to pinpoint the best traverse. Using the compass and depth gauges in Pisces it was usually possible for the geologist to locate the submersible with respect to the echo sounder traces; on some dives, however, especially where cross currents were encountered and where the features present were of a non-linear nature, the form of the sea bed recorded by the geologist did not coincide with that recorded on the echo sounder.

## The Role of Pisces in Geological Research

Pisces can carry out a range of activities under the direction of a geologist who requires no lengthy operational training:

1. Collection of samples of solid rock from chosen locations.
2. Detailed examination of rock exposures: recording of bedding, joints, foliation.
3. Detailed examination of geomorphology: recording of shapes of rock and sediment surfaces, including such features as rock overhangs and current structures in sediments. Manoeuvrability permits three-dimensional investigation.
4. Collection of sediment samples from chosen localities.
5. Investigation of relationships of different sediment facies to each other, to rock outcrops and to geomorphology; this is of value in areas of rapid lateral change.

To fulfil these roles it is essential that the sampling and photographic capabilities be reliable, and the location method satisfactory. These three systems should be perfected prior to further geological work with the submersible, and an improvement in all-round visibility would be of considerable advantage.

The hire charge for Pisces and its mother ship was £1050 per day. This is approximately the same as the cost of the shallow rotary drilling vessel M. V. Whitethorn, operated by Messrs G. Wimpey for IGS, and some three or four times that for 24-hour operation of the smallest practicable offshore sampling vessel. The future use of Pisces must depend on its cost, results and safety in relation to other methods.

Pisces is not in competition with the drilling capability of Whitethorn, but it is worth remembering that a reliable sample from an underwater outcrop collected by other methods may be of equal geological importance to a rock sample obtained through drift by Whitethorn. Where there is a heavy scatter of glacial detritus, samples of solid rock from gravity corers and dredges are suspect. In these conditions the only reliable alternative to fairly heavy drilling techniques is to use visual methods to ensure that actual outcrops are sampled. This means using divers, unmanned submersibles or manned submersibles; each of these methods has advantages and disadvantages.

Divers have maximum mobility, but are limited by safety and weather considerations. For British conditions they are at present most effectively used in shallow water, particularly in areas where sampling ships cannot venture.

A simple unmanned submersible with limited manoeuvrability close to its descent point is regarded as most likely to satisfy the routine requirement for a rapid, safe, relatively inexpensive, 24-hour, all-weather means of examining and sampling the sea floor. This is the primary requirement at the present stage of reconnaissance survey of the UK shelf, and development of such equipment is in hand. Pisces is seen as being complementary to such a vessel in that it provides a facility for thorough three-dimensional examination of localities of special importance and of type localities from which conclusions can be drawn for extrapolation into areas covered by more routine survey. The work described in the present account has substantially assisted the evaluation of data previously available, and a useful by-product has been that the team concerned has had an opportunity to become familiar with the environment in which ship-borne sampling equipment is required to work.

The relative merits of Pisces in relation to an unmanned vehicle of comparable manoeuvrability

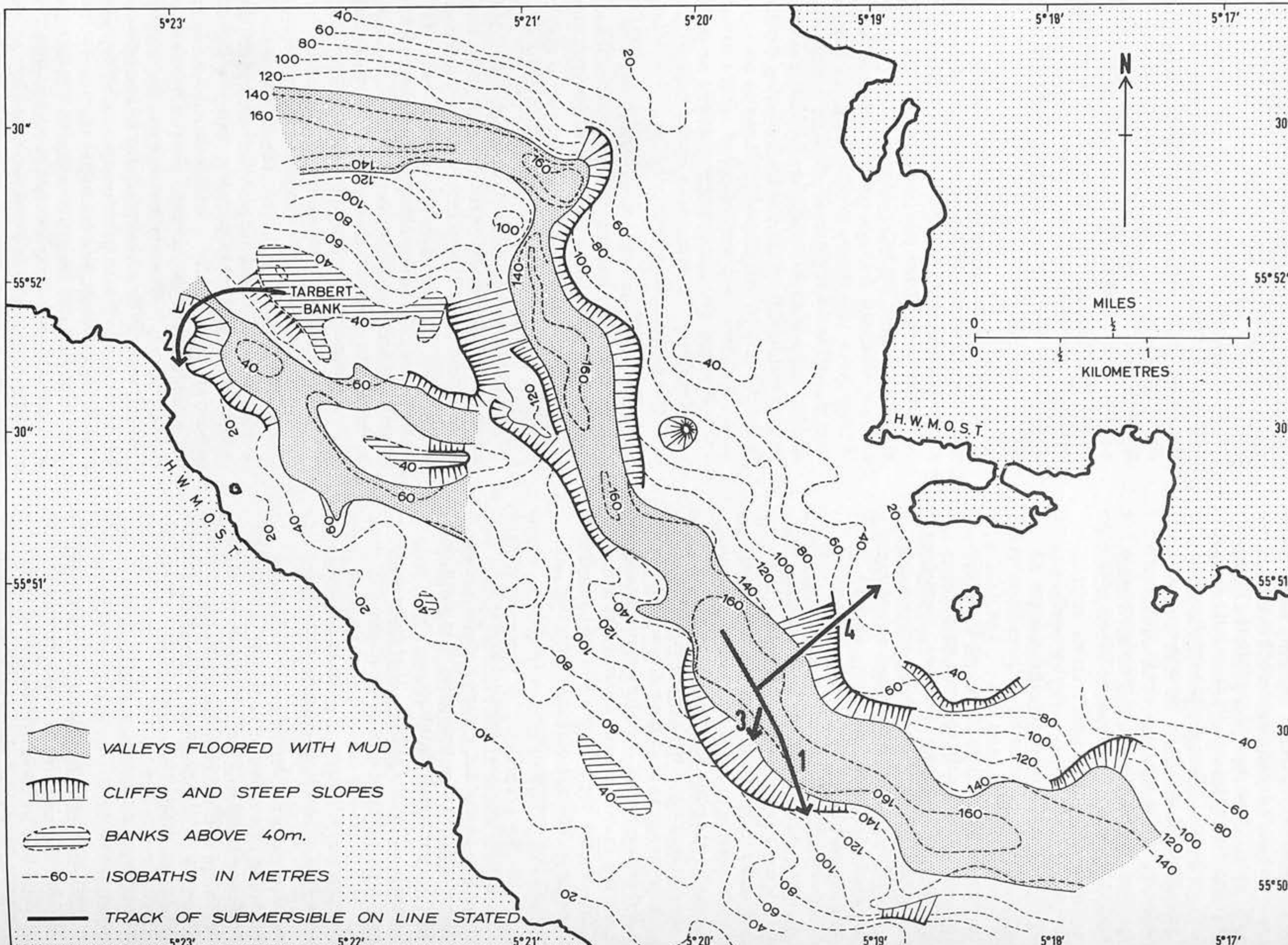



Fig. 2. Lower Loch Fyne. Traverses 69/1 to 4. Location map and bathymetry.

are not considered here, as no such submersible is at present available in the UK. It is to be noted, however, that the geological requirement is not for a fast moving vehicle, but for one like Pisces which can be traversed slowly up to, around and over features, so that stereo photographs and samples can be taken under conditions of good attitude control.

### Safety Aspects

Pisces has been constructed with safety as a primary consideration. It was operated efficiently and without serious incident during the periods of NERC charter. Nevertheless, the vehicle is designed to work in a hostile environment in which there are potential hazards which cannot be controlled. These include unexpected deterioration of weather causing recovery problems, entanglement in wreckage or cables on the sea floor, and danger from abandoned explosives. Such risks, remote as they may be, are unavoidable in the use of a manned submersible. Crew conditions and training standards and decisions as to what method to use, must take account of them, bearing in mind that some hazard is attached to most human activities.

A free diving submersible in British waters might at times be beyond available help in the unlikely event of being trapped on the sea floor. This contingency is perhaps an acceptable risk in pioneering operations, but not in routine duties, and steps to avoid it are the concern of both charterers and operators. A manned submersible for standard use requires an efficient emergency location and recovery or escape system; the form which this takes is a matter of techniques and finance, and the subject is being kept under constant review.

## LOWER LOCH FYNE

Three of the four dives in which the authors took part in Lower Loch Fyne in 1969 (69/1, 3 and 4) started in the central over-deepened area some 5 km south-east of Tarbert (Fig. 1 and Fig. 2) and one (69/2) on Tarbert Bank. The submersible at this time was not fitted with any special sampling or photographic facilities, so that work was limited to observation and photography through the thick perspex of the portholes using the submersible's searchlights for illumination.

Following the traverses with Pisces, an echo sounder survey was run by M. B. Stella Maris in the same area in order to set the observations in their bathymetric context. The results of the echo sounder survey are incorporated in Fig. 2. Two traverses across the area with 1000 joules sparker equipment, carried out by the Marine Geophysics Unit of IGS from M. V. Moray Firth IV in May 1969, are illustrated in Fig. 4.

### Traverses Across Central Overdeepened Area (69/1,3,4)

#### *THE CENTRAL MUD PLAIN*

In the area of the dives the plain is somewhat over half a kilometre wide, and depths vary from an observed maximum of 185 m below mean sea level in the centre to approximately 158 m at the margins. The middle of the area is a flat which gives way imperceptibly to a slope increasing fairly rapidly to about 15° at the foot of the surrounding cliffs (Fig. 3).

The sea floor sediment includes a high proportion of clay-grade material which rises into suspension extremely easily. When the submersible first landed on this surface seven minutes elapsed before the mud cloud dispersed sufficiently for the sea floor to become visible, and during this period the searchlights of the submersible filtered through water to which the mud cloud gave a strong peaty colour. The first landing was during slack water; at other times tidal currents carried the mud cloud away rapidly and it was observed that a current of about one knot was locally able to lift and transport a fine haze of sediment in its bottom 10 mm. When tidal currents were active a great deal of light suspended material was seen to be in lateral movement at all depths, with no noticeable tendency to settle. Much of the suspended matter was dead organic material. Scour marks were not seen in process of formation, but vague hollows up to 5 mm deep and several centimetres across were locally aligned with the current, and scours up to 10 mm deep were seen around obstacles such as rare clam shells; in places there was a suggestion of a 'micro-sastrugi' pattern. Despite these observations the mud bottom seems to be fairly stable. On two occasions when excavations were made with the handling arm or the submersible skids, it was noted that a sharp change of colour from brown to grey was visible at a level 1 mm below the surface; excavated material came out as a jumble of angular semi-cohesive fragments, not as a slurry. In places numerous unoccupied trails and apparently unoccupied burrows had a fresh appearance.

Burrows noted are of three types. Firstly, the commonest are burrows about 10 mm in diameter; many of these have an orifice surrounded by grey material thrown up from below the surface. Occasionally a puff of sediment was seen to be ejected from these holes as the occupants took abrupt avoiding action on the approach of the submersible. Secondly, burrows of the crustacean Nephrops occur in scattered colonies of three or four with about a foot between adjacent holes. Each

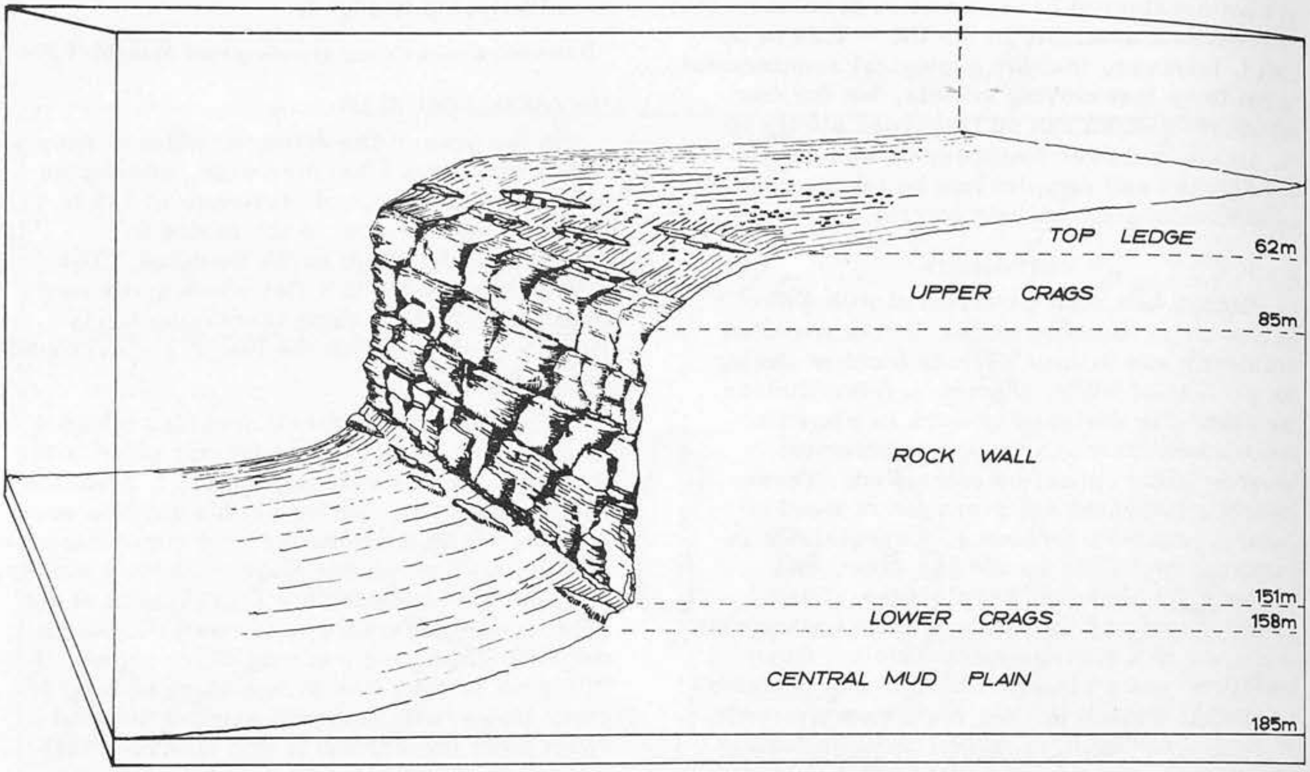



Fig. 3. Artist's impression of the rock wall on the north-east side of Lower Loch Fyne. True-to-scale drawing compiled by G. A. Goodlet from photographs and descriptions.

comprises a considerable crater, up to some 100 mm deep, with an inner burrow leading off sideways at the base of the crater; their inhabitants were observed in hasty retreat on several occasions. Thirdly, there are less common unidentified burrows 50 mm wide and 20 mm deep.

Trails noticed fall into two categories: fairly straight trails averaging about 50 mm wide and 5 mm deep, apparently formed by the common whelk (Buccinum undatum) locally seen in place at their ends, and wandering trails about 10 mm wide and 150 to 300 mm long on which no occupants were seen. Other benthonic animals which might occasionally form markings or trails were a few spider crabs up to 250 mm across, rare bottom-living fish and locally common small brittle stars and small swimming scallops.

Manganese nodules were first recorded in the area by the M. V. Mallard late in the 19th century (Buchanan, 1892; Murray and Irvine, 1894), and Dr. Calvert and Dr. Price of Edinburgh University are currently studying them in material collected by dredge and gravity corer (Calvert and Price, 1970). Samples have also been collected by IGS using a grab and dredge. Some nodules are pale brown in external colour and average about 15 mm in diameter; others are black and average 5 mm in diameter. In the course of the observations from the submersible, nodules of the larger type were not positively identified, but mud humps about 20 mm wide and 2 mm high were seen which may mark the positions of such nodules. The humps are rare, but in places are distributed at a density of about $10/m^2$. The smaller black nodules are locally very abundant, lying on the surface with a spacing varying from nothing to 20 mm; they are invariably covered with a thin dusting of sediment, except where they have been freshly thrown out of burrows. It is clear that burrowing animals help to keep the nodules at or near surface despite any sediment accumulation.

Shell debris observed falls into three categories:

1. Intact shells of local benthonic molluscs; these include a few common whelks, but the majority are of small scallops about 25 mm in diameter. Such scallop shells are almost invariably present at a fairly wide spacing (0·5 to 1·0 m) but there are patches in which they probably make up nearly 50 per cent of the surface sediment, and similarly living

scallops of comparable dimensions are locally abundant. Like the larger queen scallops (Chlamys opercularis) in shallow water, these animals are extremely active, immediately swimming off when disturbed.

2. Whole shells derived from the top ledge (Fig. 3); these are rare, but include large scallop shells (Pecten maximus) and a few crustacean fragments. Jumbled silt-tubes (about 70 mm x 7 mm) near the edge of the mud plain are inferred to be the remains of burrows which have been washed down from the top ledge or intermediate levels. The Pecten shells were observed to provide footholds for large sea anemones and clusters of whelk eggs.

3. Comminuted, white, thin-shell debris is almost ubiquitous. The fragments are angular and range in size from 1 to 5 mm, their distribution on the surface being patchy, separation varying from 5 to 50 mm; in one excavation the fragments were seen to be more abundant below the superficial millimetre, but in another the subsurface material was of homogeneous grey mud. It is inferred that these fragments are the remains of shells broken up in shallow water by wave action and washed into the deep trough.

It will be apparent from the foregoing account that the nature of the central mud plain is diverse. Parameters vary independently, but the following main bottom types may be picked out:

1. Uniform brown mud with local trails and burrows, and comminuted shell debris; this type comprises about half of the area examined.
2. Brown mud with growth of tuft-like marine organisms about 20 mm high; separation of the tufts ranges from 10 to 75 mm.
3. Brown shelly mud with abundant small scallop shells.
4. Brown mud with abundant black manganese nodules.
5. Brown mud with abundant jumbled silt-tubes, seen near the edge of the plain.

*LOWER CRAGS*

At none of the three localities examined does a vertical rock wall plunge straight down at the edge of the central mud plain; in every case there is a zone in which the inclination of the sea floor increases markedly and rocky crags break through the surface (Fig. 3). The mud slopes are commonly of the order of 20° to 30° and the crag faces range from vertical to an average inclination of 45°. Small ledges on the rock surfaces are picked out by thin layers of mud, which was noted to adhere on slopes of up to 70°.

The mud slopes resemble the uniform brown mud with trails and burrows seen in the central plain; there is the same superficial layer of brown colouration over grey and the same content of small fragments of thin angular shell fragments. The preferred orientation of the trails is up and down the slope. Nephrops burrows are concentrated on small mud flats below some of the rock faces, but burrows about 10 mm in diameter are very much more abundant and present at all positions on the slope.

At 152 to 158 m depth on the west side of the central plain the mud slope was seen to give way to muddy scree, in which the lithic fragments vary from angular to subangular in shape and generally from 10 to 50 mm in diameter. Similar fragments occur not uncommonly on most of the mud slopes.

Rock exposures range in size from a few metres across to a 21-m high vertical crag. It was not possible to sample the exposures, but it was noted that the rocks are strongly foliated in a north-north-west direction parallel to the sides of the valley, the foliation dipping eastwards at about 40°. Rock surfaces are either smooth or broken along joint planes; two vertical joint directions at right angles are particularly prominent on the north side of the valley and these give rise in places to angular rock buttresses. The direction of foliation is not in accord with the NNE-SSW strike of the Dalradian strata which occupy both shores of Lower Loch Fyne in this area. Structures shown on one-inch Geological Survey Sheet 29 seem to point to the possibility of a dextral slip fault running NNW-SSE along the length of the loch, and the anomalous foliation direction observed may be associated with such a fault.

The rock surfaces are fairly bare except for large numbers of stalkless, pink sea anemones about 150 mm in diameter; in places these cover approximately 30 per cent of the rock surface, particularly at the tops of crags. Regular echinoids and 150-mm long translucent, pink prawns are not uncommon, the latter congregating below small overhangs.

*ROCK WALL*

The main rock wall on the north side of the trough was examined on traverse 69/4 where it was seen to be a roughly vertical cliff extending up from 151 to 85 m depth (Fig. 3).

Over considerable areas of the cliff no rock structures could be deciphered but locally a strong foliation following the strike of the cliff could be seen; this foliation dips at 40° into the cliff face and its truncated edges are responsible for periodical steep ledges a metre or two in width. In one or two places it could be seen that the rock has an irregularly foliated appearance, with an overall pink colouration due to the presence of abundant lenticles and streaks of pink material in a grey matrix emplaced along the foliation. The alternating grey and pink bands are of the order of 50 to 100 mm wide. As in the lower crags, vertical and other jointing was locally visible.

The overall nature of the cliff surface can be described as smoothly undulating, the scattered ledges giving a lineation apparently controlled by the foliation; no slickensiding or glacial gouging could be positively identified. In two areas smooth gentle overhangs of about two metres were noted. Only in a few places was the smooth surface broken in such a way that the rock structure could be seen; in these localities breaks were mostly angular and along joints or foliation planes. At one place gashes 0·3 m deep were developed along the foliation.

The rock wall carries a rich fauna and flora, particularly below the gentle overhangs, where sea squirts and projecting tube worms are prominent, and in the local broken patches where large prawns, squat lobsters and other crustaceans shelter in the crevices. On more exposed areas large, pink sea anemones and white sponges are noticeable.

Rare thin patches of mud were observed adhering to the ledges and with a surface inclination of 60° to 70°.

*UPPER CRAGS*

Above a depth of 85 m the vertical rock observed on traverse 69/4 gives way to a rocky slope which gradually decreases in steepness upwards (Fig. 3). The bottom part of this slope is generally inclined at 50° to 70° and comprises rock similar to that at lower levels. A 3-m wide ledge at 83 m is covered with angular gravel (fragments up to 30 mm in diameter) set in a matrix of muddy sand and a great deal of shell debris, ranging from comminuted to whole shells; the shells are mostly of small scallops similar to those in deeper water and many are blackened. There are also many living scallops of the same species.

The proportion of the sea floor occupied by sediments of this type increases upwards and the slope of their surface eases off to about 4°. In the more muddy parts are seen many burrows of about 10-mm diameter, from which grey material has been ejected over the superficial brown layer; there are rare Nephrops burrows.

As the sea floor slope decreases the steep crags at lower levels give way to low mounds and platforms of smooth rock with a few low near-vertical faces on the seaward side. The rock is commonly covered with a dusting of mud and comminuted shell debris, both on the flats and adhering to slopes of up to 50°. Sea anemones are somewhat smaller than at lower levels, but in places they cover as much as 25 per cent of the rock surface. The presence of a thin layer of light sediment explains the frequent collection of small quantities of this material when a sampling grab is lowered onto a submarine rock outcrop.

*TOP LEDGE*

Above a depth of 62 m on traverse 69/4 the sea floor with rock exposures was observed to give way to a uniform sediment-covered slope of some 2° or 3° with rare smooth rock patches in the deeper parts (Fig. 3). The sediment shows considerable lateral variation, including mud, muddy gravel, shell accumulations and spreads of boulders up to half a metre in diameter. Most of the boulders are well-rounded, but there is a great deal of angular and subangular gravel-sized material. Upwards to 35 m, at which depth Traverse 69/4 was terminated, the boulders give way to subangular cobbles and then to less common patches of muddy, angular gravel surrounded by spreads of brown micaceous mud in which shell debris is locally abundant.

The fauna on the top ledge includes abundant living queen scallops (Chlamys opercularis) some 50 to 60 mm in diameter; shells of these and a variety of other forms of similar size are abundant, both scattered over the surface and in shell accumulations. Comminuted shell debris and angular fragments are also common. In general both the whole shells and shell fragments are much larger than those at lower levels. Feather stars are abundant on the cobble and boulder-covered surfaces and the mud areas have trails and burrows similar to those noted in deeper water.

### Traverse from Tarbert Bank to Coast (69/2)

The course of the submersible during traverse 69/2 approximated to a parabola commencing on a heading of N 320° but becoming increasingly south-westward due to progressive compass drift and the effect of a strong current (Fig. 2).

The traverse commenced on the Tarbert Bank at a depth of 27·5 m where an approximately level sediment cover of muddy sand, shells and gravel was encountered, with a fauna predominantly composed of brittle stars. From this vicinity a short slope increasing to an angle of 30° and covered by sand, shell, gravel and numerous boulders was found to lead up to a

2-m high rock step beyond which the rock slopes more gently upward to the top edge of a westerly facing cliff. The cliff is a near-vertical rock wall dropping from approximately 20 m to a depth of 50 m where the slope of the wall eases to an average of about 30°, with some sections sloping at 45°, before reaching a mud plain at 70 m.

A current, estimated to be more than 2 knots and running approximately from north to south, was experienced on the mud plain. After traversing this plain for a short distance the submersible collided with a rock wall in poor visibility and a sample of quartzite chipped off in the collision became lodged on the torpedo claw, from which it was recovered after the dive. No marked increase in slope was noticeable before reaching the rock, which appears to have been about 5 to 10 m high.

Above the wall an area of sand with many boulders gives way to a sandy mud area sloping down again to the mud plain at 70 m. From this second section of the plain a moderate slope with shell debris, including many whole valves, leads up to a lower set of rocky crags with gravel and some boulders on the intervening slopes. Above these crags a rock wall trending NNW to SSE rises to a depth of 45 m where a rocky area, showing numerous joints and areas of sand with much shell debris, slopes upwards towards the shore. This was followed up to a depth of 10 m, where the traverse was terminated.

It appears, therefore, that the area traversed conforms in most respects to that seen in the inspection of the profile across the central over-deepened area. The top of the Tarbert Bank is comparable with the top ledge, while the margins of the bank and the shore area are to be equated with the upper crags. Both lead downward to a rock wall, lower crags and a mud plain. Apart from the smaller scale of the features a notable difference is that in this area there is a rock exposure in the centre of the mud plain, marked by the crag with which the submersible collided; this exposure had the suggestion of a small scale crag-and-tail structure.

### Comment on Dives in Lower Loch Fyne

The sparker profiles (Fig. 4) show that the rock walls examined in traverses 69/1, 3 and 4 constitute the top part of a U-shaped valley incised into the floor of the Loch, the bottom part of the valley being filled with drift with ill-defined indications of roughly horizontal bedding (Fig. 5). The sediment thickness seen in the deepest parts of the troughs cut by the sparker profiles reaches a maximum of about 150 m. Locally a sharp V-shaped notch is seen on the profiles in the base of the U-shaped hollows in this vicinity. Only in the central mud plain was any appreciable thickness of drift detected, but the sparker system in use would not be expected to pick out drift patches less than about 10 m thick; it is probable that in places, particularly in the hollows running south and west of Tarbert Bank, several metres of drift are in fact present.

The bathymetry and sparker profiles taken together show that appreciable overdeepening has occurred below the central mud plain. The floor of the most northerly hollow of this plain lies for example about 40 m below the floor of the 'col' to the south of it, and the rock bed is overdeepened by at least 25 m in relation to the rock bed below the 'col'. The spectacular right angle bend at the southern end of the most northerly hollow is to be noted. Sedimentation is tending to fill in the hollows, but the infilling is not complete and is apparently proceeding at a very slow rate.

The two hollows south of Tarbert Bank are tributaries to the central hollow, but the bathymetry indicates clearly that they are hanging valleys, both of them terminating at the top of steep slopes.

Lower Loch Fyne occupies a broad valley rising steeply to surrounding hills to east and west (only the western hills are shown in Fig. 5). The floor of the valley is an undulating surface, partly submerged, into which is cut the U-shaped valley described.

The only form of erosion able to produce landforms such as these is ice action, probably aided by subglacial water acting under hydrostatic head which is likely to have been responsible for the V-shaped notch locally seen in the floor of the main rock hollow, and which may have acted as a spearhead to the downcutting action of the ice. The initiation of a hollow running in this NW-SE direction may have been due to weakness along a fault plane, as in the case of the Great Glen. The generally smoothly undulating nature of the rock wall, and the presence of local plucked areas, is characteristic of ice rather than water erosion; the district has been subject to multiple glaciation, and similar sequences of ice erosion and melting must have occurred in each glaciation.

It is of interest that the U-shaped valley lies well below present sea level, and lay still further below contemporary sea level during glaciation, when the land was isostatically depressed by its ice load (Sissons, 1965). It cannot, therefore, have been formed by a valley glacier, but must have been cut by differential erosion by a stream of ice within an ice sheet; the same consideration applies to the tributary hanging valleys south of Tarbert Bank.

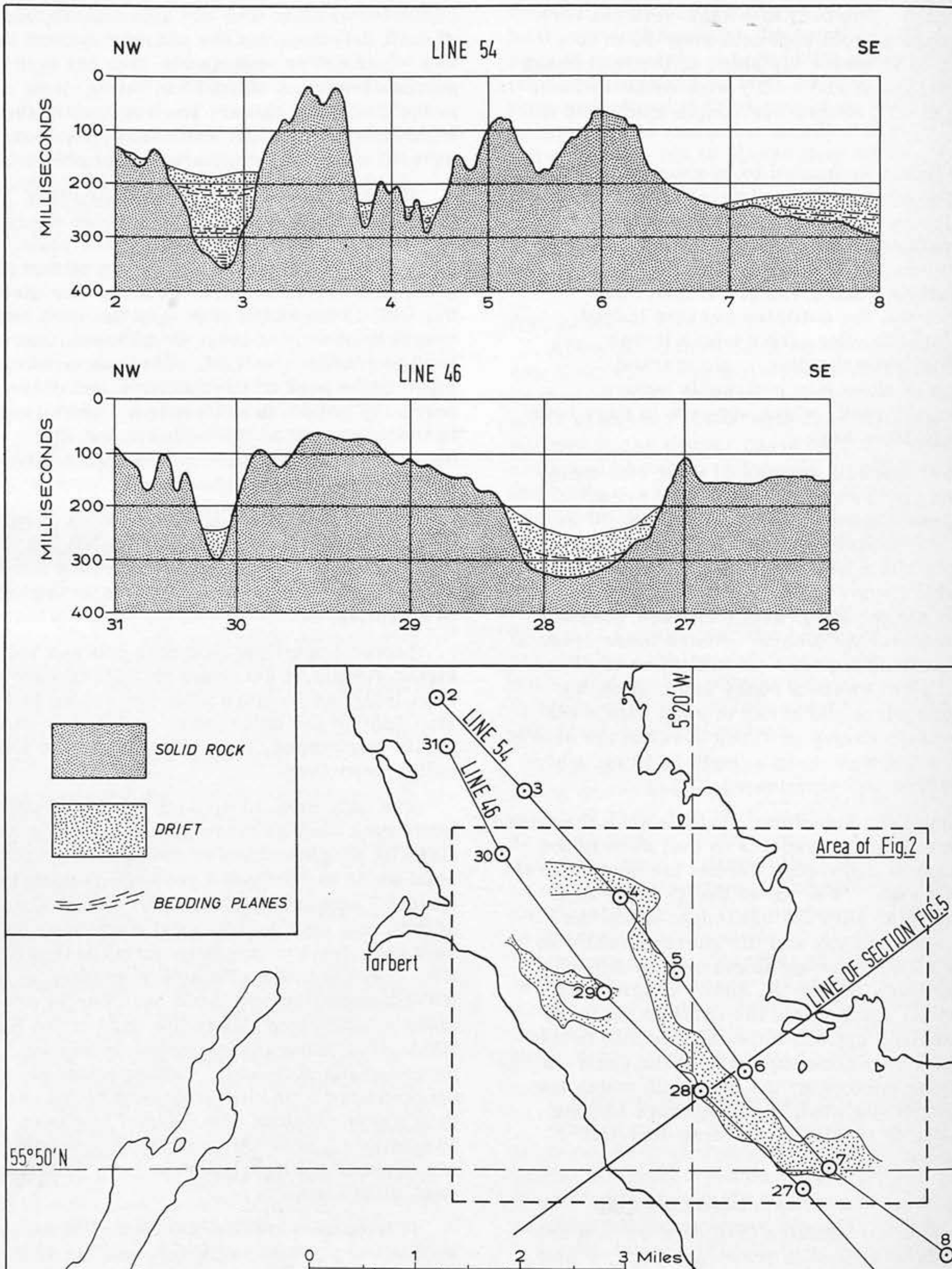



Fig. 4. Sparker traverses along Lower Loch Fyne.

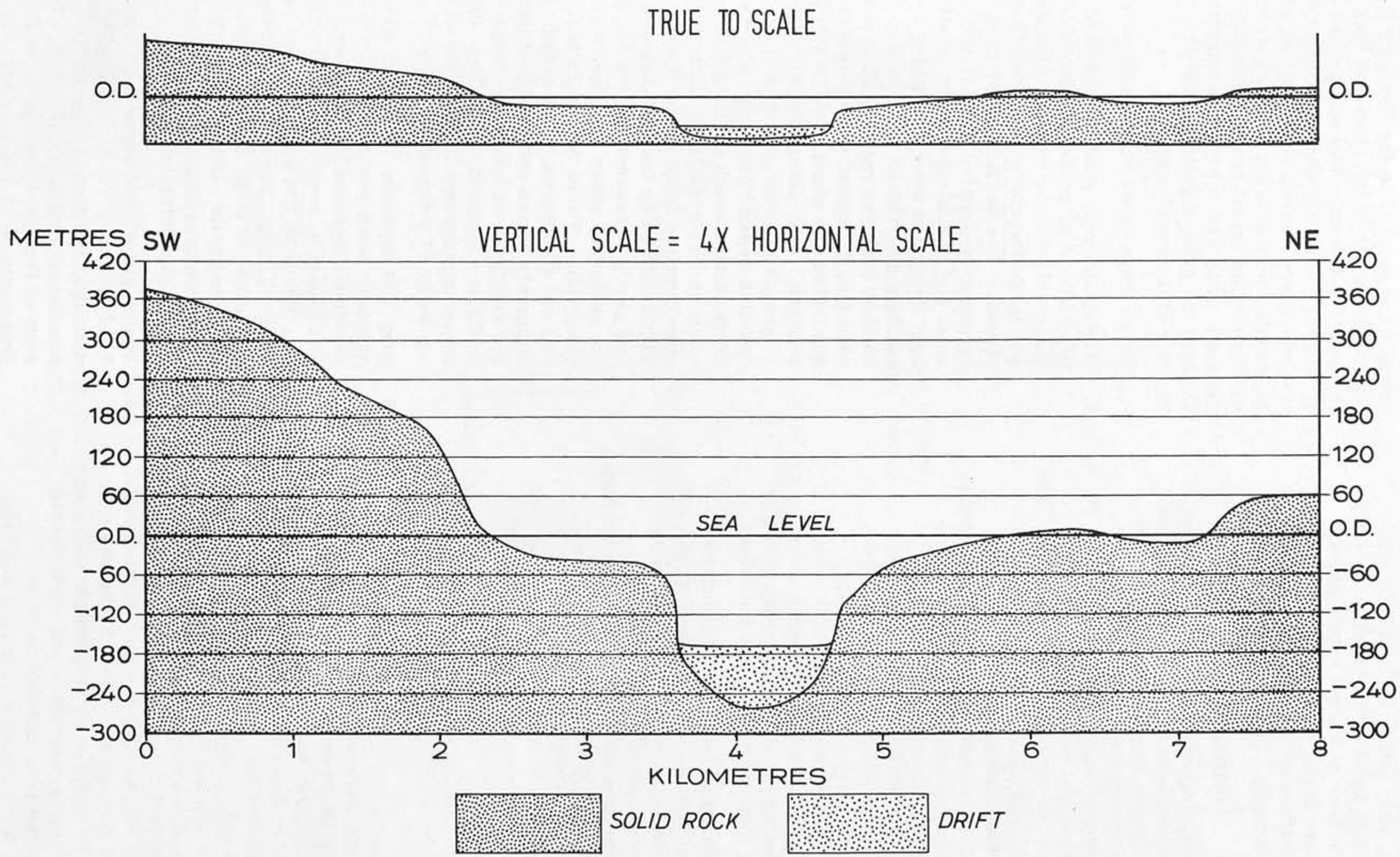



Fig. 5. Section across Lower Loch Fyne.

A fast moving ice stream ('ice stream A') within the present Antarctic ice sheet has been described by Robin (1958, Fig. 62) and Swithinbank (1959, p. 104, and p. 117). This ice stream, which is believed to be differentially excavating its floor at a level approaching 800 m below sea level, appears to exemplify the type of mechanism which caused the land forms demonstrated in the floor of Loch Fyne.

## FIRTH OF LORN

Most of the planned diving for the second cruise was in areas inaccessible for work on the first day from a suitable port. The two dives in the Firth of Lorn (Fig. 6) were, therefore, added to the programme as shakedown exercises near to Oban, Argyll, where the vessels were mobilised. The dives were sited in an area of irregular topography which had not previously been sampled as it is crossed by three transatlantic telephone cables spaced in such a way as to make normal surface sampling methods difficult. Both dives were short because available time was limited; the first was planned to investigate a deep undulating area in the main channel of the Firth 4 km west of Insh Island, and the second a steep rock wall forming the eastern margin of the main channel 3 km north of the same island.

The television and external and internal camera systems were tried out during the dives, but because of rather poor visibility and initial instrumental difficulties only limited success was obtained. The submersible sediment samplers and rock levers and baskets were used experimentally, one sediment tube sample was recovered, together with a number of loose rock fragments which were picked up with the handling arm.

The occurrence of boulders and other lithic fragments in the vicinity of rock outcrops suggests that here, at least, deposition is slow, since the water depth is such that these materials are likely to have been undisturbed since emplacement by glacial agencies. In deeper water away from outcrops, however, active deposition of mud and shell material is occurring; this was well observed at location 70/1A.

### Recent Sediments and Dyke Outcrops West of Insh Island (70/1A)

The traverse followed the centre of the main channel of the Firth. There was a gentle south-westerly rise throughout. Most of the sea floor was found to be covered by fine muddy sediments with some gravel-grade lithic and shell debris, but two elongated rock exposures were encountered; the first was examined and then passed on its southern flank, the second was climbed and proved to be a rock step about 2 m high (Fig. 6). Both exposures are of hard massive rock with a few visible joints and with smooth north-east facing scarps sloping uniformly at about 45°. Since the exposures are aligned parallel to the Tertiary dykes of Mull and Lorn it is inferred that they belong to the same swarm. The scarps are planed smooth by glaciation and no loose in situ fragments were seen, so it was not possible to sample them with the handling arm. It was noted that small brachiopods adhered to the rock faces with a preferred orientation aligning the gape of their shells with the contour of the rock.

Three main types of sediment were observed:

1. Brownish sandy mud with variable proportions of broken unsorted shell fragments which, with the exception of one large Buccinum, are less than 30 mm across. The surface of the mud has an irregularly dimpled appearance. The most common bivalves are small scallops, both living and dead, the living individuals patchily distributed at about $5/m^2$; other benthos includes rare small crustaceans, rare small regular echinoids and widely separated sun stars, brittle stars and other starfish. A striking feature is the presence of groups of roughly oval polychaete colonies resembling large white cobbles; there is also much fluffy hydroid growth a few centimetres long. Scattered small open burrows were seen; the dimples are partly caused by the collapse of the burrows and partly represent the resting places of the scallops, which were not active when observed. There are no indications of current structures. The sediment is uniformly brown and unconsolidated in the few centimetres below the surface which could be examined, indicating that the contemporary sea floor is possibly the top layer of a deposit in active formation.

2. Shell flat deposits. A 100-m wide spread of muddy shell material above the upper rock wall includes up to 75 per cent of whole shells, mostly small living scallops; individuals of the same species are abundant, about $50/m^2$. There is a variable admixture of mud, locally scattered thinly over the shells, and the shell flat merges south-westwards into the shelly mud with the dimpled surface.

3. Muddy gravel and scree-like deposits. Thin wedges of ill-sorted muddy 'scree' extend up the front of the rock scarps and similar material forms a belt a few metres wide at the top of the upper wall. Rock fragments, up to 150 mm across, are angular and subangular. A few rounded cobbles are scattered at the foot of each rock slope but normally mud butts directly

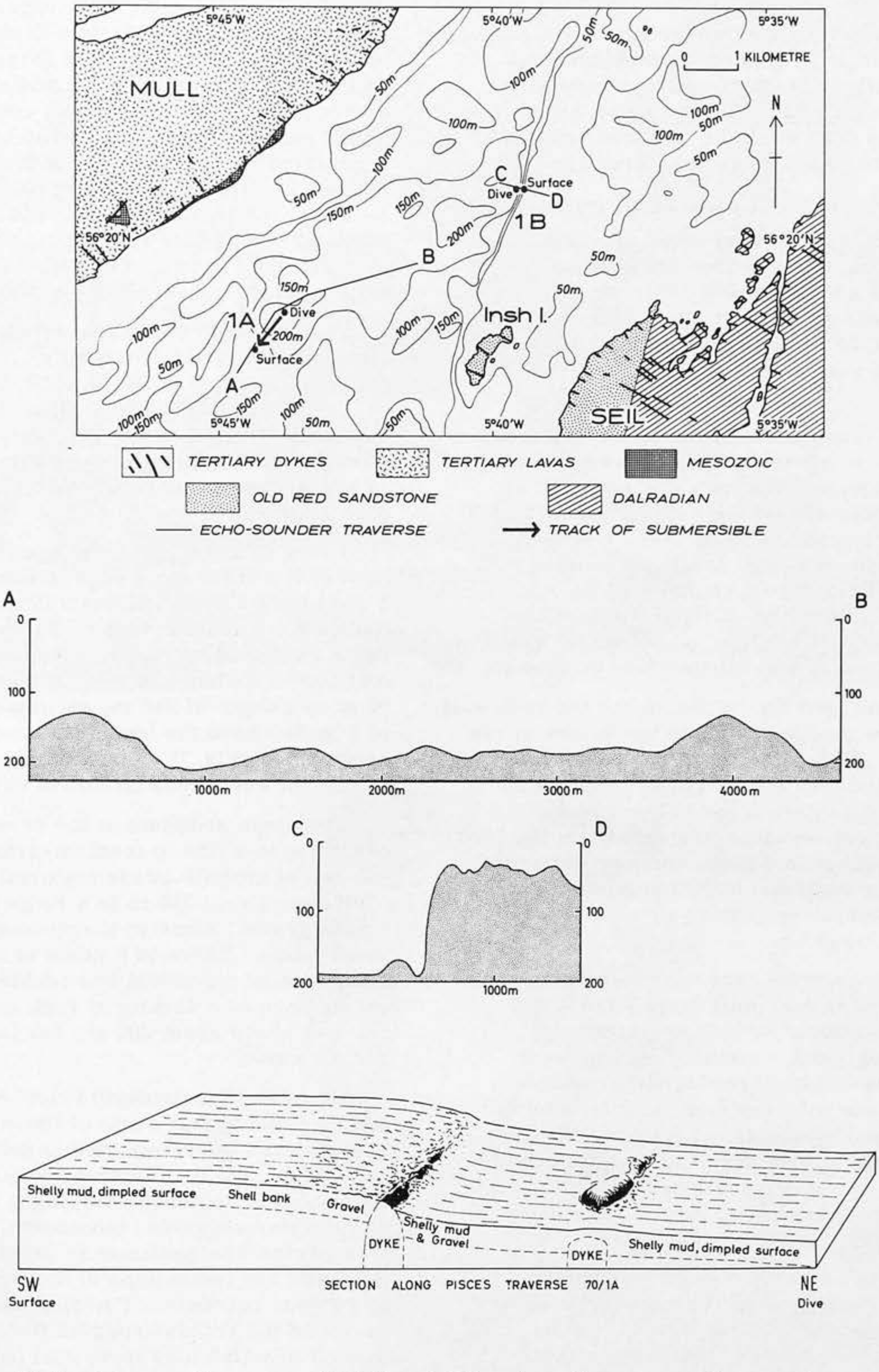



Fig. 6. Firth of Lorn. Traverses 70/1A and 1B. Location map, echo sounder sections and artist's impression.

against rock or sloping 'scree'. Scree-like deposits are not being formed under present conditions and so are inferred to be of possibly glacial origin.

Country rock was nowhere seen. Geophysical traverses show an apparently structureless material, with a magnetic pattern consistent with the presence of Tertiary dykes, but drilling through thin drift would be required to identify the rock into which these are intruded.

### The Rock Wall of Insh Island Ridge (70/1B)

The submersible descended to a depth of a little less than 200 m some 100 m from the wall of the Insh Island ridge (Fig. 6), and travelled east-south-east, first across sediments and then up the rock wall which constitutes the margin of the main glacial trough of the Firth of Lorn.

The traverse commenced on a level area of brownish sandy mud with scattered, very fine shell debris. Burrows are abundant on this flat, their diameters ranging from 10 to 50 mm and their spacing from 1 to $15/m^2$. A current estimated at 25 cm/sec was observed running from N 30° but no discernible orientation structures could be made out on the sea floor. Nephrops, a few small scallops, rare small crabs and brittle stars were seen.

From the mud flat to the foot of the rock wall progressive changes occur in the nature of the sea floor. First, the slope increases gradually and then more rapidly to reach 25° at the foot of the scree apron below the cliff. Secondly, rare boulders protrude from the mud surface, and become more common upwards. Thirdly, the sediment becomes gradually coarser, with an increasing proportion of large shell detritus.

Beyond a narrow zone of boulder scree a near-vertical rock wall rises from some 100 m to a depth of 82 m. A narrow mud covered ledge with a slope of 40° was seen near the base, but otherwise no structure could be made out in this cliff. It is inferred from the geology of adjacent islands that the cliff is likely to comprise Old Red Sandstone lavas, but no sampling was possible with available equipment because of the smoothness of the vertical face.

At a depth of 82 m contact with the cliff was lost and because of shortage of time the dive was terminated. The pre-dive echo sounder survey showed, however, that the slope eases off slightly at about this depth and continues to decrease to the crest of the ridge at 35 m (Fig. 6). There is thus a close parallel between the scale and form of this submerged cliff on the south-east side of the Firth of Lorn and that of the rock wall observed in Lower Loch Fyne.

## TOP OF THE CONTINENTAL SLOPE

Two dives were made near the top of the continental slope about 80 km west-south-west of Barra Head (Fig. 1); they together constitute a continuous traverse from a depth of 381 m eastward to a depth of 160 m (Fig. 7). The object was to investigate the sedimentary environment at the edge of the continental shelf and in particular to examine the low irregularities and north to south elongated patches of hard ground shown near the shelf edge on Precision Depth Recorder and sonar records obtained during NIO work in the area in 1968. The NIO joint author of this account, Dr. J. B. Wilson, was present on one of the dives.

A feature of the two traverses was the remarkable clarity of the water. It proved possible to motor at 160 m with the floodlights of the submersible extinguished, using available daylight only. Visibility without the floodlights at this depth was estimated to be 13 m; ascent and descent were through clear blue water.

Prior to diving, an echo sounder traverse showed the continental edge to comprise here a wide flat between 130 and 145 m deep, with low swells up to 6 m high. Seawards of this flat a westward increase of slope sets in, so that over a distance of 3 km the sea floor falls 50 m to a depth of 210 m, an average incline of 1 in 60; here the low swells are more accentuated (Fig. 7). Below 210 m there is a uniform westwards incline of about 1 in 20.

The slope sediment at the deeper levels examined is a fine to medium-grained sand with patches of granule-grade material and isolated boulders; above 230 m is a large spread of cobble gravel, some of it extremely compact, some loose. There is a north to south elongation of individual low cobble ridges. The cobbles are of a variety of rock types, well-rounded above about 200 m, but less so in deeper water.

Because of their depth below sea level it seems unlikely that some of the coarser lithic material can be transported in present day conditions, and it is inferred that sea floor deposition is not now occurring. The clarity of the water suggests, moreover, that little transported fine sediment is crossing the area, but there are indications of movement of sand by contour currents. The disposition and nature of the cobbles suggest that the deposit of which they form part has been subject to heavy wave action, possibly at a time of lower sea level. The origin of the lithic material is inferred to be glacial.

The cover of epifauna on the lithic material is generally less than at other dive sites, and it was sometimes possible to identify rock types

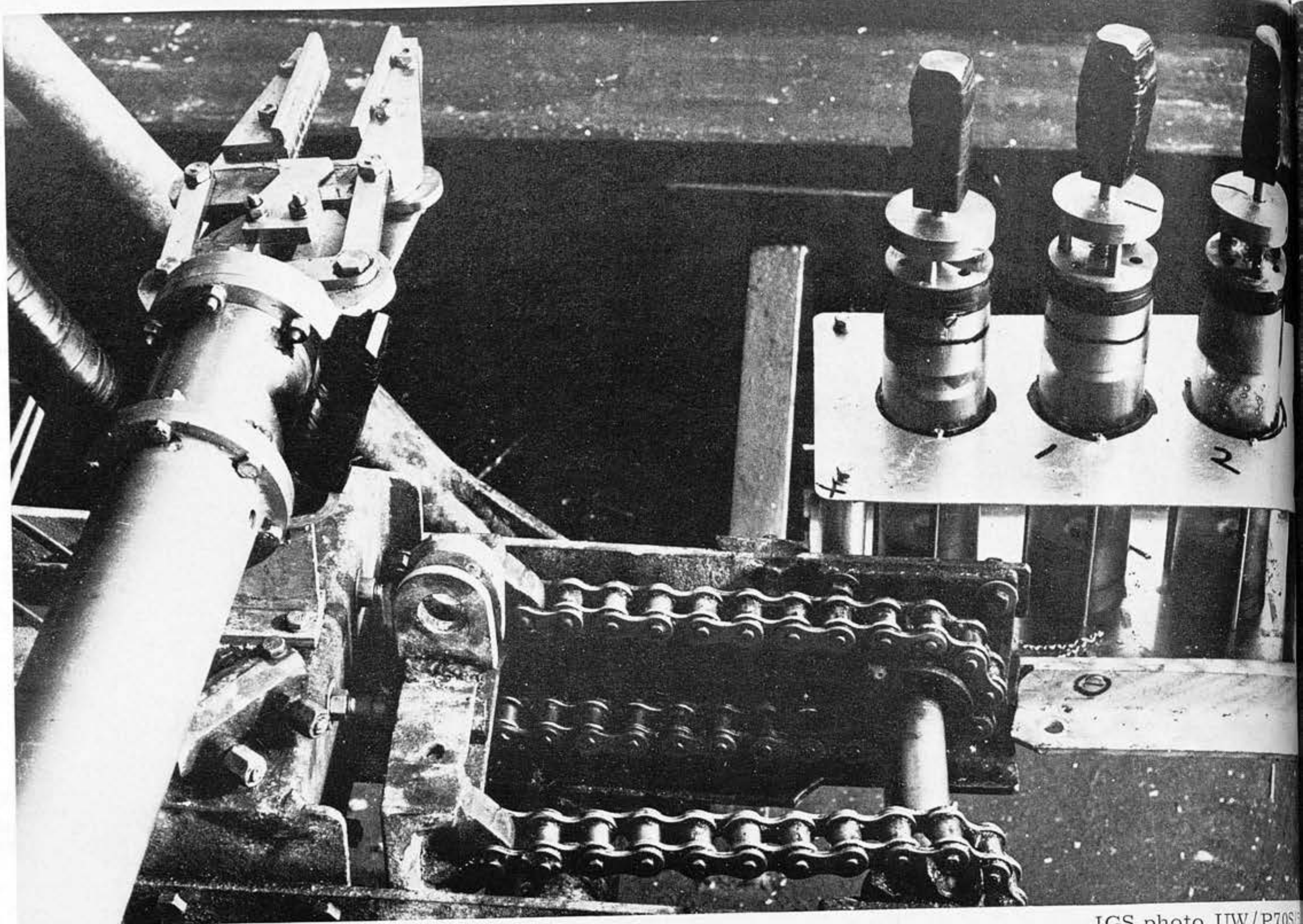

Photo by Vickers Oceanics.

PLATE 1

1a. R. V. Vickers Venturer and Submersible Pisces.

IGS photo UW/P69S/1.

1b. Pisces suspended from A-frame prior to launching in Lower Loch Fyne.



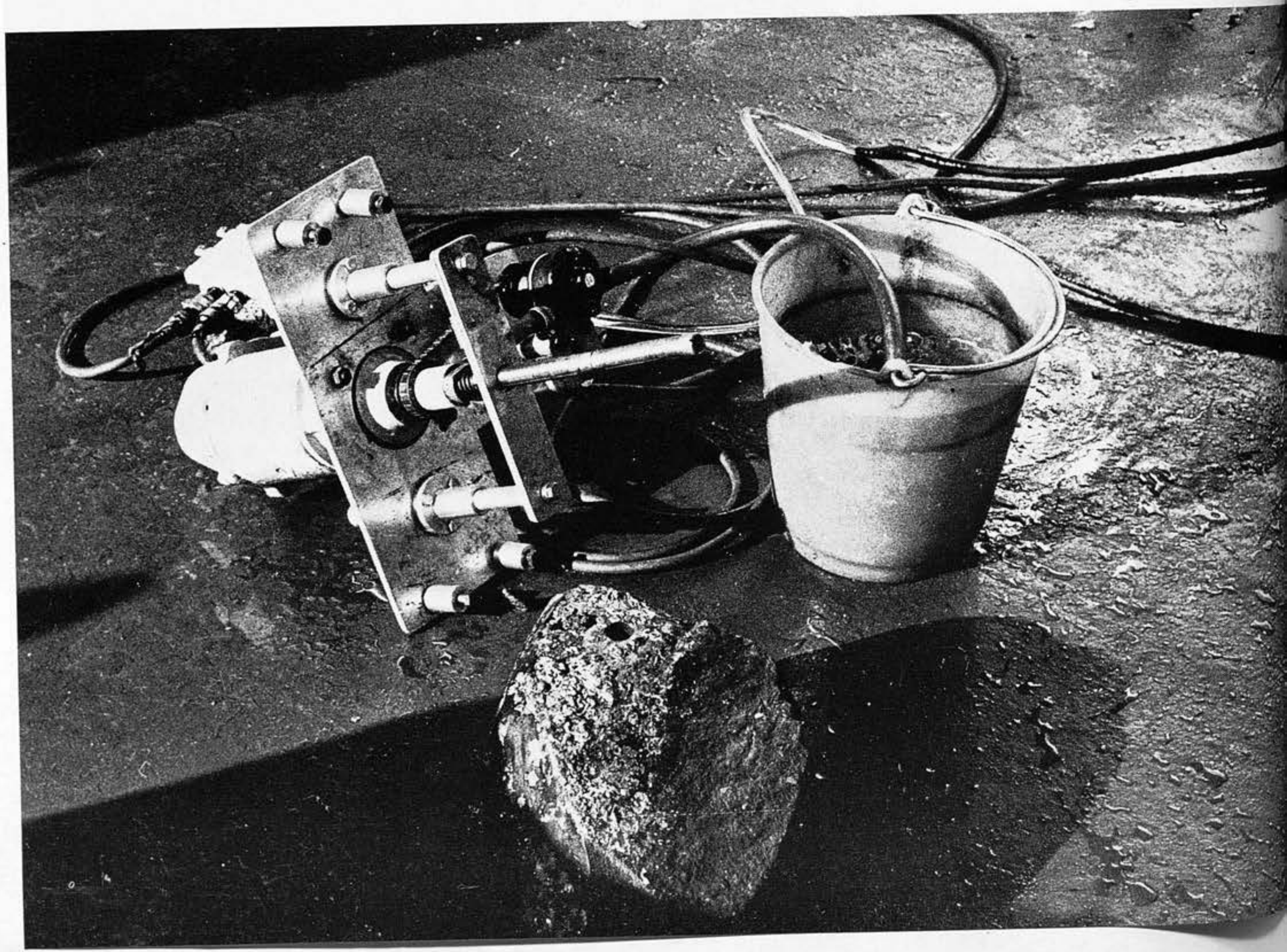
IGS photo UW/P70S/

2a. Handling arm and sediment samplers mounted on Pisces.

PLATE 2

2b. Rock drill as tested on deck prior to mounting on Pisces.

IGS photo UW/P70S/



IGS photo UW/P70/2A/38.

3a. Sand and gravel at the top of the continental slope. Traverse 70/2B. Depth 230 m. Note the sand shadows indicating transport from south to north.

PLATE 3

3b. Cobble gravel at the top of the continental slope. Traverse 70/2B. Depth 200 m.

IGS photo UW/P70/2B/19.

IGS photo UW/P70/3B/9.

PLATE 4

4a. Morainic material in process of submergence in mud. Ridge in trench east of Outer Hebrides. Traverse 70/3B. Depth 100 m.

4b. Crinoid field on shelly mud. Trench east of Outer Hebrides. Traverse 70/3B. Depth 100 m.

IGS photo UW/P70/3B/3.


GS photo UW/P70/4A/24.

5a. Angular scree at foot of submerged cliff. Stanton Banks. Traverse 70/4A. Depth 91 m.

PLATE 5

5b. Jointed Lewisian rocks of Stanton Banks. Traverse 70/4A. Depth 75 m.

GS photo UW/P70/4A/3.


IGS photo UW/P70/4A/10

PLATE 6

6a. Glaciated pavement on Lewisian rocks on Stanton Banks. Traverse 70/4A. Depth 70 m.

6b. Starved sand ripples. Stanton Banks. Traverse 70/4B. Depth 77 m.

IGS photo UW/P70/4B/17


IGS photo UW/P70/5A/19A.

7a. 'Submerged beach' on Blackstones Bank. Traverse 70/5A. Depth 70 m.

PLATE 7

7b. Jointed and bedded Torridonian strata in the Inner Sound. Traverse 70/8A. Depth 100 m.

IGS photo UW/P70/8A/3A.

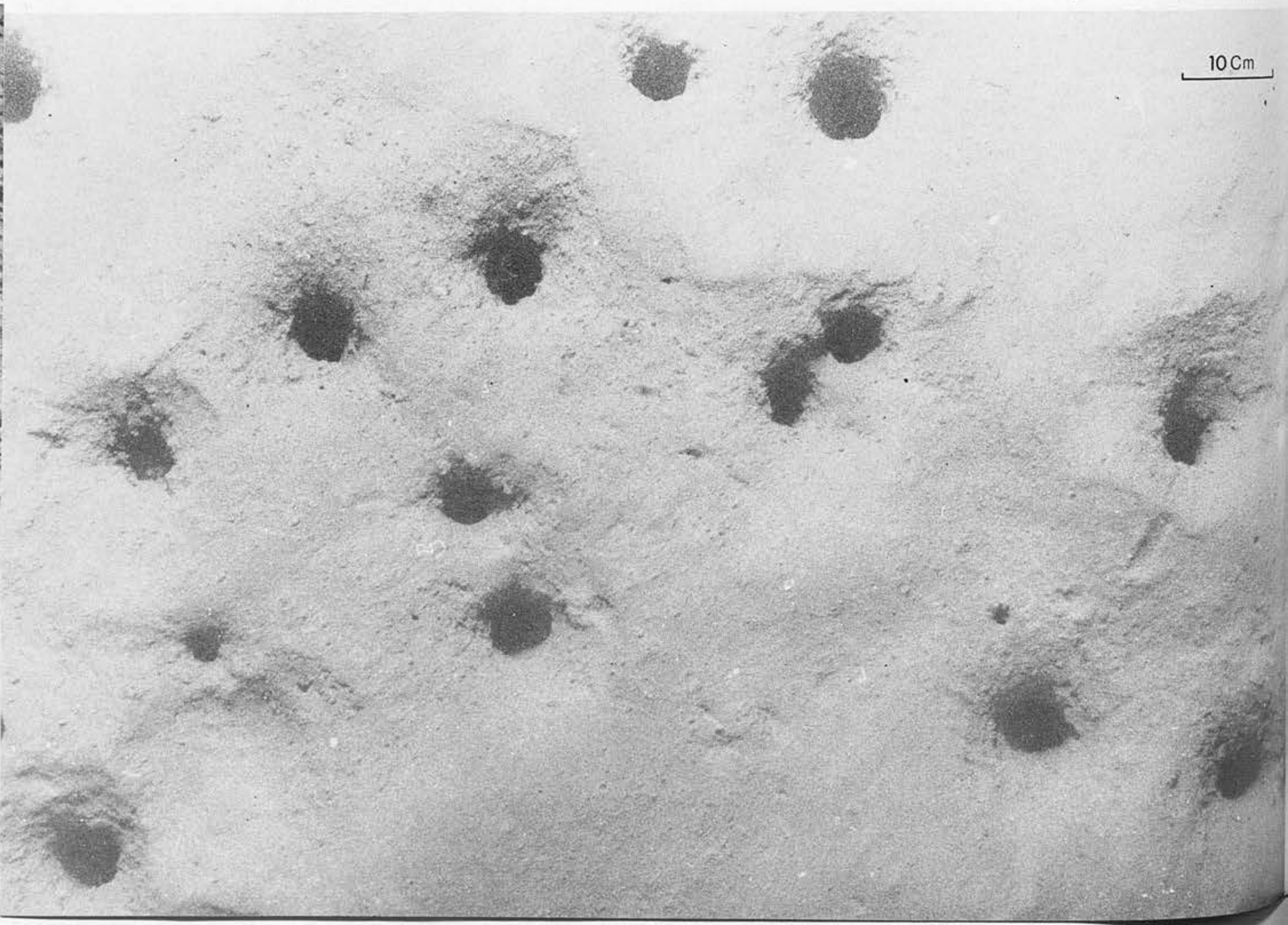

IGS photo UW/P70/9A/1.

8a. Morainic debris on Hawes Bank. Traverse 70/9A. Depth 50 m.

PLATE 8

8b. Nephrops and Calocaris burrows in Sound of Jura. Depth 80 m. Photograph with IGS marine camera from R. V. Clupea.

IGS photo UW/CL70/7R3.



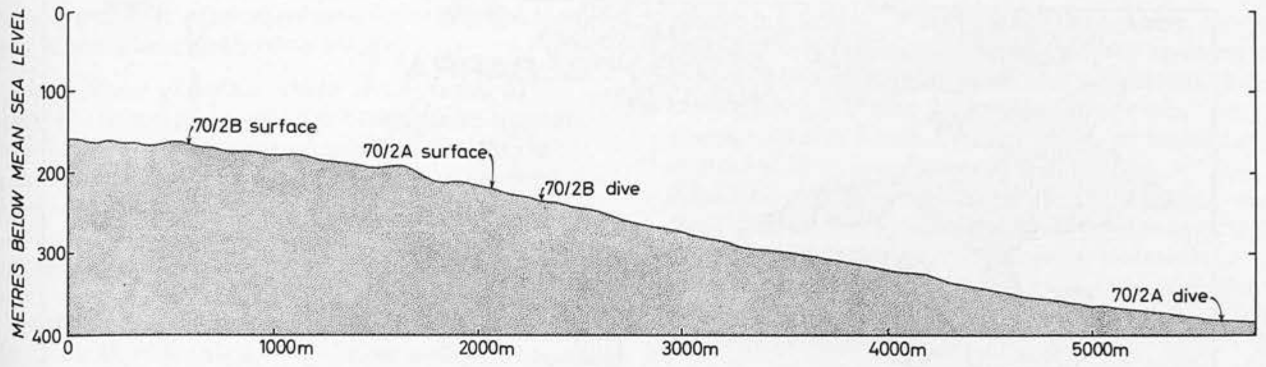



Fig. 7. Top of the continental slope. Traverses 70/2A and 2B. Echo sounder section.

visually.

Irregularities and inclines on echo sounder records are greatly exaggerated and the slope down into the North Atlantic basin in this area is in fact so gentle as to be almost imperceptible when observed from the submersible, as are the irregularities of up to 6 m seen on the echo sounder traces.

Video tape and photographic records were made during the two dives, but a temporary failure of the handling arm, due to a blockage in its hydraulic feed, prevented any extensive sampling of the cobble bed. The second dive had to be terminated due to power failure on the submersible.

### Sandy Deposits of the Upper Part of the Continental Slope (70/2A)

The submersible descended to the sea floor at a depth of 381 m and travelled a net distance of 3. 5 km eastwards up the slope (Fig. 7) reaching a depth of 215 m.

The sediment on which the submersible landed is a light coloured sand, apparently of fine to medium grade. Shell and lithic fragments up to 30 mm across lie scattered on the surface together with black ovoid faecal pellets up to 5 mm long.

This surface is typical of that encountered throughout the dive, but farther up the slope, patches of coarser material also occur. Normally these patches are irregular, but in places form discontinuous stringers oriented roughly parallel to the contour. Most of the coarse-material is of granule or pebble grade but locally areas of subangular to subrounded cobbles up to about 200 mm diameter are found. Isolated cobbles and boulders seen include one rectangular boulder a little over one metre across. A distinction could be made between black fragments, probably basic igneous rock, and lightish brown fragments; one of the latter was picked up with the handling arm and later found to be a reddish brown homogeneous mudstone.

At a few places along the traverse, ripple marks were observed. These have an amplitude of 30 to 60 mm and wavelength of 70 to 100 mm. Some of the smaller ripples are poorly defined but a general east-west trend can be distinguished. In one area the submersible crossed a system of larger ripples also with a general east-west trend. These have an amplitude of 1 to 2 m and a wavelength of 6 to 8 m; the smaller ripples on their crests are exceptionally well developed and are asymmetric with steep sides facing north. The troughs of the larger ripples contain coarse pebble-grade shell and lithic debris.

### Cobble Beds on the Continental Edge (70/2B)

On the second dive the submersible reached the sea floor at a depth of 230 m to continue the eastwards traverse of dive 70/2A. The bottom crossed on this dive was similar to that encountered on the first although there was a much higher proportion of gravel-grade material, especially cobbles. Four types of sea floor could be distinguished, but a complete gradation between the types was observed:

1. Cobble gravel, very well compacted, as if it had been rolled flat, with a few loose cobbles and boulders scattered over the surface of the compacted material.
2. Spreads of loose cobbles (Plates 3a and 3b).
3. Ill-sorted mixed sand and gravel with clusters of boulders.
4. Spreads of comparatively well-graded gravel, fragments about 20 mm in diameter.

Much of the material is well-rounded, but angular and subangular cobble-sized fragments also occur; rock types observed included gneiss, dark basic rock and red sandstone. A red mudstone fragment recovered with the handling arm was later found to have a partial cover of grey bryozoan growth together with a number of small solitary corals. The bryozoan growth

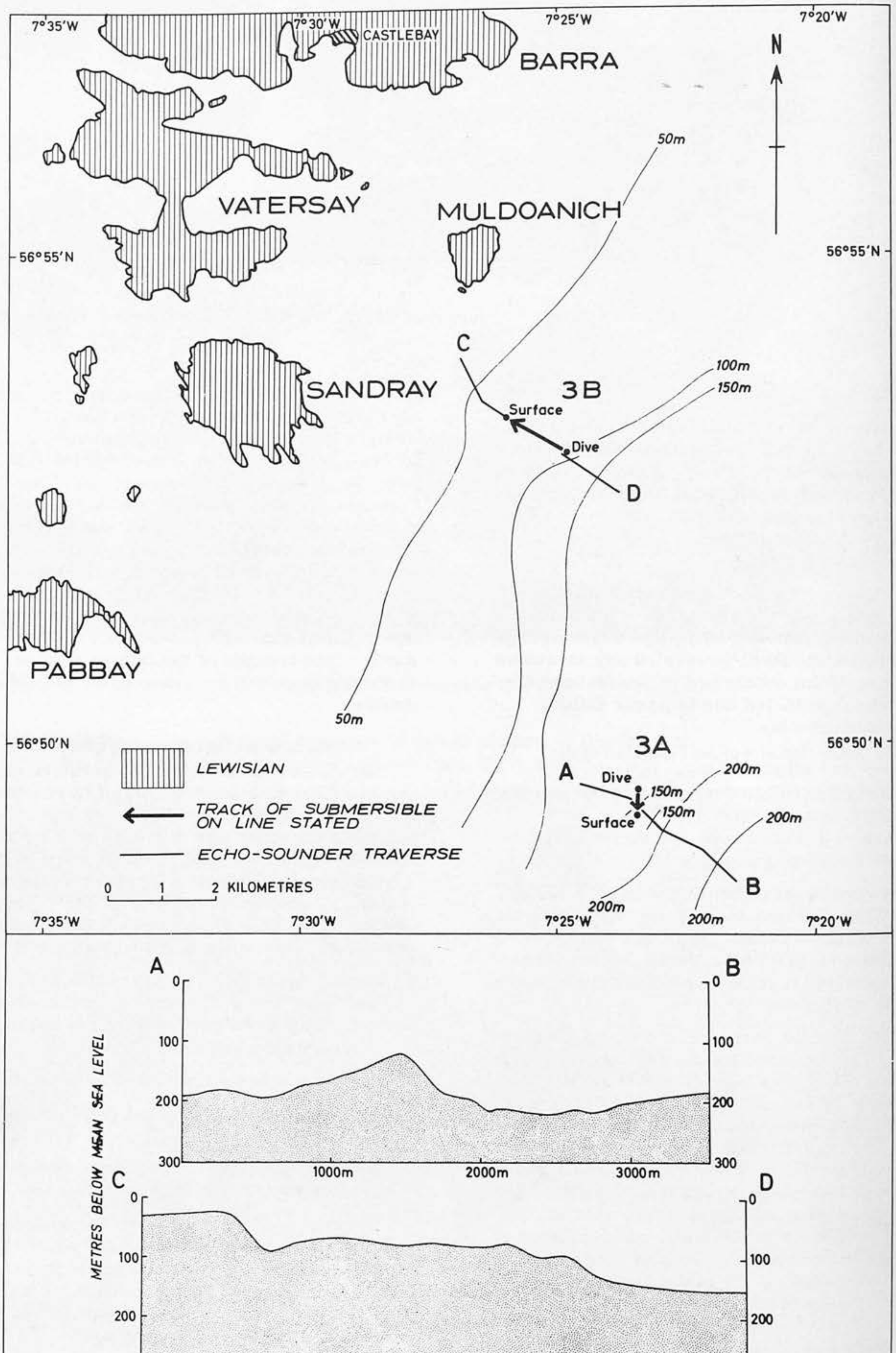



Fig. 8. Area south of Barra. Traverses 70/3A and 3B. Location map and echo sounder sections.

gives a general grey appearance to the cobble beds when observed under water.

A number of small scale indications of south-north orientation in the sea floor deposit were observed and photographed: 1. Slight scour marks lying in a south-north direction in small sandy patches. 2. Sand tails to the north of obstructions and scours to the south, suggesting emplacement by a current from the south (Plate 3a); at their most distinct these tails are up to about 1 m long, 150 mm wide and 20 mm thick. 3. Low cobble ridges, up to nearly a metre across and 200 mm high, best seen in the areas of loose cobbles.

At the time of the dive there was a current estimated at 12 cm/sec from the south; sediment was not observed in motion, but the sand streamers indicate that sand is at times able to travel in this direction along the contours.

It is inferred that the material of the cobble beds was transported to its present site primarily by glacial action, either being deposited as end moraine or from melting of floating ice. The beds do not, however, resemble the winnowed top of glacial till which has been recorded in some areas, and the predominance of well-rounded material, clear indications of sorting in places, and the low cobble ridges all point to the importance of wave action in the late stages of their formation. The bryozoan film on the lithic fragments suggests that these may be stationary and their ridge-form a fossil feature dating from a time of lower sea level.

### AREA SOUTH OF BARRA ISLAND

One of the marked bathymetric features of the Sea of the Hebrides is the overdeepened hollow running in a general NNE-SSW direction a few kilometres east of the Outer Hebrides (Fig. 1). North of Barra Island there appears to be a simple slope up from the centre of the hollow onto the Lewisian platform of the Outer Hebrides. Farther south the bathymetry is more complicated; IGS geophysical work has, for example, revealed that the trough is divided in places by NE-SW trending ridges of ? Lewisian rocks. The area of deep water has been referred to as a former river valley by Ting (1937) and has been related to the position of the Minch Fault by Dearnley (1962) and McQuillin and others (in preparation). Ice movement across the Outer Hebrides was at one stage east to west (Jehu and Craig, 1925), but at some period movements appear to have been diverted south-south-west by the island chain to overdeepen the hollow.

Two dives were made to investigate the geomorphology of the western flank of the deep water area (Fig. 8), the first near the centre, and the second on an apparently stepped Lewisian topography farther inshore. A coral colony was located and examined, but on neither dive was any solid rock seen, mainly due to a widespread cover of stony material of a morainic nature. Slow deposition of silty shelly mud is occurring on flats and depressions, gradually submerging the morainic debris in the areas examined. Several loose cobbles were collected with the handling arm, and photographic and video tape records obtained.

#### Coral Colony and Morainic Deposits in a Trench East of Barra Head (70/3A)

The dive was planned to investigate the geology and topography of an area inferred from 1968 IGS sparker and magnetometer data to be floored by level-bedded strata with Lewisian inliers, and also the nature of a coral colony first located in 1968 by Dr. J. B. Wilson working with the R. R. S. John Murray. Dr. Wilson's earlier observations and those made during the work described here are detailed in Appendix 2. It was found that the underlying solid rocks are everywhere obscured by morainic material or thick epifauna. Experience to date is that such a thick cover of epifauna is unusual off the Scottish coasts except in very shallow water.

The dive was preceded by a series of closely spaced echo sounder runs; the results have been incorporated into Fig. 8, which also shows an echo sounder line (A-B) at right angles to the main features of the topography. The deeper hollow is the centre of the complex trough east of the Outer Hebrides. The isolated ridge shown on line A-B runs NE-SW; the coral colony investigated lies on the crest of a steep sided 10-m-high bank striking at N 120° on the top of this ridge, that is, in the same direction as the echo sounder trace, on which it is not seen.

After Pisces had dived, its Decca main chain location relayed from R. V. Vickers Venturer indicated that submergence was slightly north of the target position and the submersible, therefore, proceeded across the sea floor on a bearing of N 180°.

The traverse first ran obliquely up a gentle slope covered by morainic material with mud patches, until it reached the foot of the 10-m bank referred to above. The north side of the bank slopes at 30°; the south side was not well seen but appeared to be steep. Along the traverse, this bank is everywhere encrusted with thick organic growth (Appendix 2), so the rock type could not be determined, but the bank may owe its form to an igneous dyke or sill. The dive was terminated at the crest of the bank and the submersible was recovered close by, at Decca Navigator (chain 6C) position F22·45: A30·4: J60·3.

The gently sloping sea floor along the first part of the traverse lies on the north-west of the NE-SW ridge shown on line A-B, Fig. 8. Numerous patches of ill-sorted boulders, cobbles and gravel occur; most of the fragments are subrounded to subangular and well embedded in the surface, but some of the more rounded boulders stand clear. There is an ubiquitous cover of silty mud, which varies from a thick scattering over the stony surface to a layer covering all but the tops of a few of the larger boulders. Shelly flecks are common in the mud and locally, where excavated around boulders by crustacea, it is seen to contain silt tubes formed by burrowing organisms. No current-orientated structures were observed. Although the mud rises easily into suspension it proved to have a firm consistency when scraped with the handling arm. The stony material is the top of a spread of glacial origin which shows no indication of modification by wave action; at the present day it is being slowly submerged by silty mud. A striking feature of the area is the presence of numerous mobile crinoids, described by Dr. Wilson in Appendix 2. These tend to be concentrated at the tops of boulders, but are also well distributed over stony and muddy surfaces alike.

### Stepped Lewisian Topography South of Barra (70/3B)

The object of this traverse was to examine the geomorphology and sediments associated with two south-east facing escarpments (line C-D, Fig. 8) which form the submerged margin of the Lewisian complex of the Outer Hebrides. The dive was preceded by an echo sounder and Transit Sonar survey which indicated that rock exposures were widespread on the westerly escarpment, and 'hard ground' on the easterly escarpment and on the irregular shelf between the two. The Pisces traverse was confined to this irregular shelf.

Two NE-SW boulder ridges were crossed near the east side of the shelf, apparently situated at the top of the easterly escarpment. Each ridge is about 5 m high and 10 m across, and they are separated by a hollow 30 m wide, with its base at 105 m depth. Detritus on the ridges ranges in size up to boulder-grade, the boulders being largest and most abundant towards the tops, where they are up to 1 m across. All lithic material is predominantly subangular with an ubiquitous film of mud (Plate 4a); samples collected with the handling arm proved to be of Lewisian rock. Sediment around and between the two boulder ridges is muddy sand with much shell debris including scattered gastropods; burrows are distributed at about $25/m^2$, and there are numerous depressions apparently formed by infilled burrows; mobile crinoids are locally abundant (Plate 4b). At the edges of the boulder ridges this sediment slopes upwards with an inclination of as much as 40° on the eastern sides but less on the western sides, giving way upwards first to more shelly sediment and then to the stony material of the ridges. Numerous small octopuses were noted in the area between the ridges.

The crest of the more westerly of the two ridges lies at 85 m; westwards the traverse crossed a 250-m wide flat of muddy sand at 90 m rising gradually to a third similar boulder ridge with a crest at 80 m. Clams and crabs were noted in the vicinity of this third ridge.

Westwards of the third ridge the sea floor is occupied predominantly by muddy sand sloping up irregularly from 90 to 75 m at the western end of the traverse. In this distance of about 800 m, four low mounds of unsorted boulders, cobbles and gravel were encountered.

The mounds and ridges of rock fragments are inferred to be morainic accumulations in process of being buried in a spread of muddy and shelly sand, but it is not known whether or not they have cores of solid rock. No clear indications of sediment-transport direction were observed.

## STANTON BANKS

Stanton Banks are extensive rocky and stony shoals lying 60 km south of Barra Head (Figs. 1 and 9). They were chosen for investigation because they provide an example of unusually rugged submarine topography some distance from land and because it was hoped that the work would confirm that the banks are formed of Lewisian rocks, as suggested by their position on the prolongation of both the Coll-Tiree and Outer Hebrides Lewisian ridges, and by 1968 geophysical data.

A recent, detailed Admiralty survey shows the north-western corner of the banks to have the strongest relief. Predicted tidal currents required a north-easterly course on the first dive in this area and a south-westerly course on the second. Three parallel echo sounder runs were carried out before the dives to help position the sites in relation to the Admiralty survey.

Along both traverses the terrain is similar. A large glaciated area, similar to those which occur in the Highlands but here swept clean of any cover, is divided by hollows and gullies with coarse shell sand and fringed by aprons of boulders and cobbles. Two samples were collected from broken in situ rock with the handling arm before it was put out of action. Both samples were of coarse-grained granite, inferred to be of Lewisian age.

Visibility in the area was excellent, ambient light being strong and the water free of fines. Good quality photographic and video tape records were obtained (Plates 5 and 6). Large brittle stars were notably abundant on all rock faces.

Rock Gully Topography on the NW Edge of Stanton Banks (70/4A)

The traverse started in 91 m of water amongst the scree (Plate 5a) at the foot of the rocky slope shown at the south-west end of the echo sounder section A-B, Fig. 9. The net horizontal distance travelled was about 1 km and the topography as recorded from the submersible agreed with that on the echo sounder trace. Apart from the floors of the three hollows shown on the section and a number of smaller ones not shown, the terrain is rocky and, although rounded by glacial action, is fissured and extremely rugged. The hollows are bounded by crags varying from vertical to steeply stepped. Scattered boulders and cobbles occur in places on the rock surface, but large areas are swept clean of any deposit (Plate 6a).

There appears to be an erosion level at between 80 and 90 m, since this is the depth of the rock platforms and cobble-covered flats which floor some of the gullies, while fissures widened by erosion occur down to this depth.

A fractured piece of rock was picked out with the handling arm of the submersible;

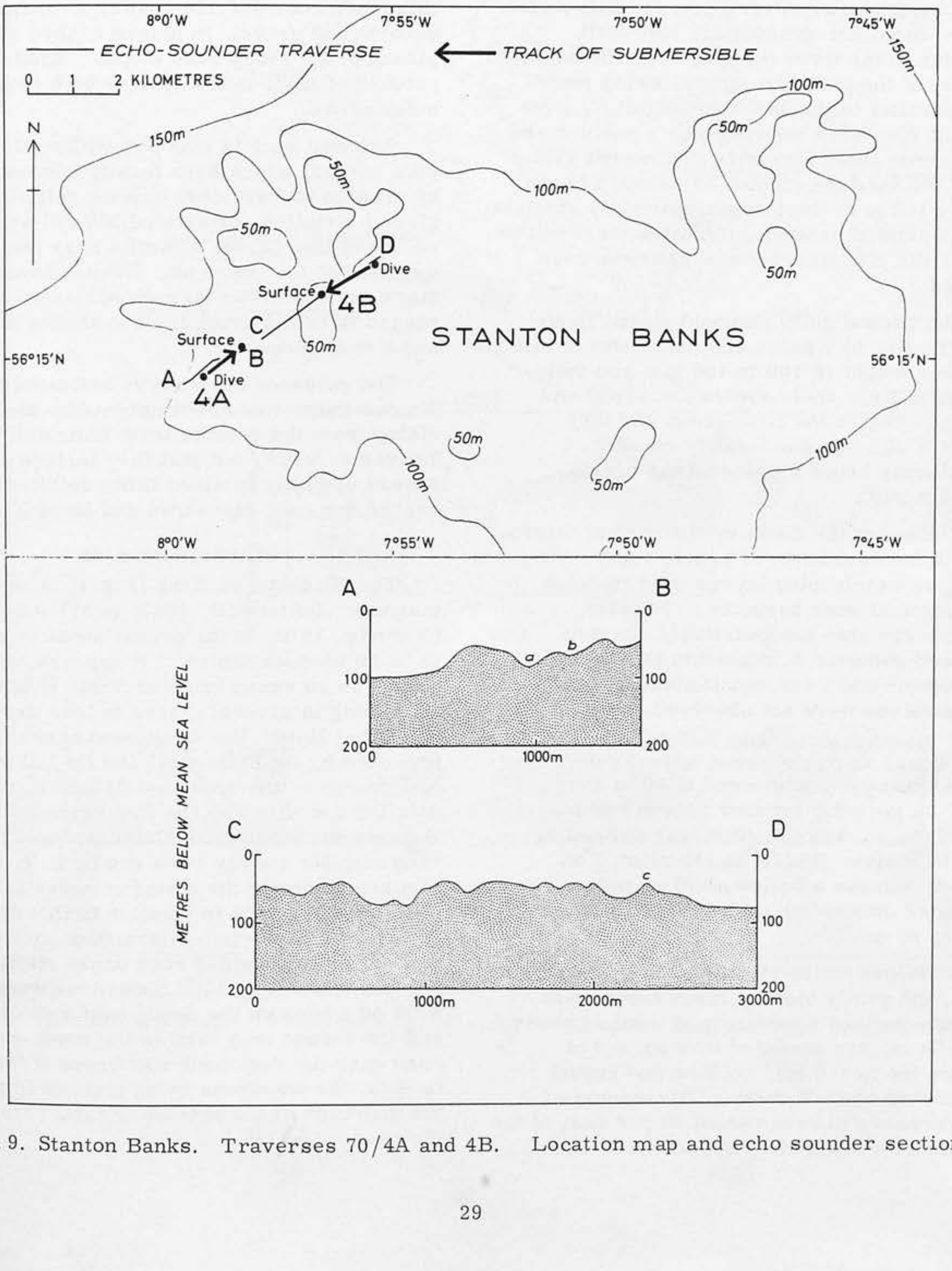



Fig. 9. Stanton Banks. Traverses 70/4A and 4B. Location map and echo sounder sections.

although all faces are covered with epifauna this fragment (a coarse granite probably of Lewisian age) is believed to have been in situ. It is to be noted that in spite of very good visibility the ubiquitous cover of epifauna made it impossible to examine the texture of the rock whilst on the sea floor (Plate 5b).

Two broad areas of coarse, whitish shell sand formed into prominent ripples were observed in gullies during the dive, and elsewhere similar material was seen in cracks and crevices in the rock. At position a on line A-B, Fig. 9, the ripples are symmetrical and discontinuous, about 100 to 150 mm high and 0. 75 m in wavelength, trending from east to west, normal to the gully wall. The sand is here coarse to very coarse, with minor granule to cobble-grade lithic and shell fragments in the wave troughs. On the north-east side of the gully the ripples swing round to run parallel to the N-S bounding cliff, from which the spread is separated by a boulder and cobble apron about 5 m wide. Towards this edge of the sand the ripples are about 200 mm high and 1·5 m in wavelength, normally straight and with pointed crests; bifurcations are absent but near the cliff interference patterns were observed.

In the second gully floored by sand (b on line A-B, Fig. 9) ripples also occur but in this case their height is 100 to 150 mm and their wavelength 1 m; their crests are broad and flat in contrast to the first group and they trend at N 30°. At one locality small discontinuous cross ripples on the crests trend at N 170°.

A feature of the fauna in this part of Stanton Banks is the abundance of brittle stars, clinging in overlapping layers even to some of the vertical rock surfaces. Regular echinoids are also comparatively common. The shell sand comprises fragments of serpulids, echinoderms and a few small bivalves, but living bivalves were not observed.

### Stony Spreads and Rock Gullies in the Central NW Part of Stanton Banks (70/4B)

The traverse commenced at 90 m near point D on the echo sounder record and led obliquely up across the rock spur defined by the 50 m contour (Fig. 9) to elevation c on line C-D, across a hollow at 70 m and terminated on another rock area with peaks reaching 42 m.

The deeper water parts of this traverse, that is, the gently sloping areas north-east and south-west of elevation c at depths between 90 and 70 m, are occupied by a spread of boulders (up to 1·0 m), cobbles and gravel with patches of shell sand. The amount of sand increases to cover about 50 per cent of the sea floor at a depth of 77 m just north-east of elevation c, where very well developed symmetrical ripples in coarse shell sand occur on a flat area about 15 m across; wavelength is 1·0 m and amplitude 200 to 250 mm; some bifurcation in the ripples was observed but the general strike of the crests is NE-SW. The ripples are starved, with underlying cobbles and gravel showing in the troughs (Plate 6b).

The lowest rock exposure encountered was at 75 m; above this depth glaciated rock steps, platforms and rounded peaks were traversed. The peaks are free of detritus and covered with numerous small white sea anemones which give them the appearance of snow-clad summits. At lower levels and on rock flats and hollows there is a considerable scatter of boulders, cobbles and gravel, in places banked with slopes of 45° below rock steps. Small patches of shell sand occur on both rock and stony areas.

Exposed rock is massive with well-developed joint planes, which have locally been exploited by erosion to form deep narrow gullies. Apparent glacial striations orientated NW-SE were noted on two of the highest summits near the south-west end of the traverse. Echinoids and brittle stars are numerous on rock surfaces; epifauna ranges in colour from lilac to shades of orange and a deep turquoise.

The evidence of this dive indicates that the Stanton Banks are not simply rocky shoals rising from the erosion level indicated by Traverse 70/4A, but that they include a large spread of gently inclined lithic detritus banked around the rock exposures and lapping onto them.

## BLACKSTONES BANK

The Blackstones Bank (Fig. 1) is an area of magnetic (Bullerwell, 1963, p. 67) and gravity (Roberts, 1970, in the press) anomaly believed to be an igneous centre. It appears on Admiralty charts as an unnamed shoal about 10 km across and rising in several places to less than 25 m below sea level; the name used here is being proposed by Dr Bullerwell and Dr Roberts. The bathymetry of the area is well known from recent detailed soundings by the Hydrographic Department, Ministry of Defence, but 25 km of echo sounder survey were run by R. V. Vickers Venturer prior to the diving in order to fix dive positions precisely in relation to this data. The combined bathymetric information indicates a number of steep-sided rock banks rising from a broad shoal (Fig. 10). Two dives were made, the first on a bank on the south-east side of the shoal, and the second on a bank to the north-east. In each case the rock bank was crossed from side to side, the traverses being planned to run in the direction of the prevailing tidal currents at the time.

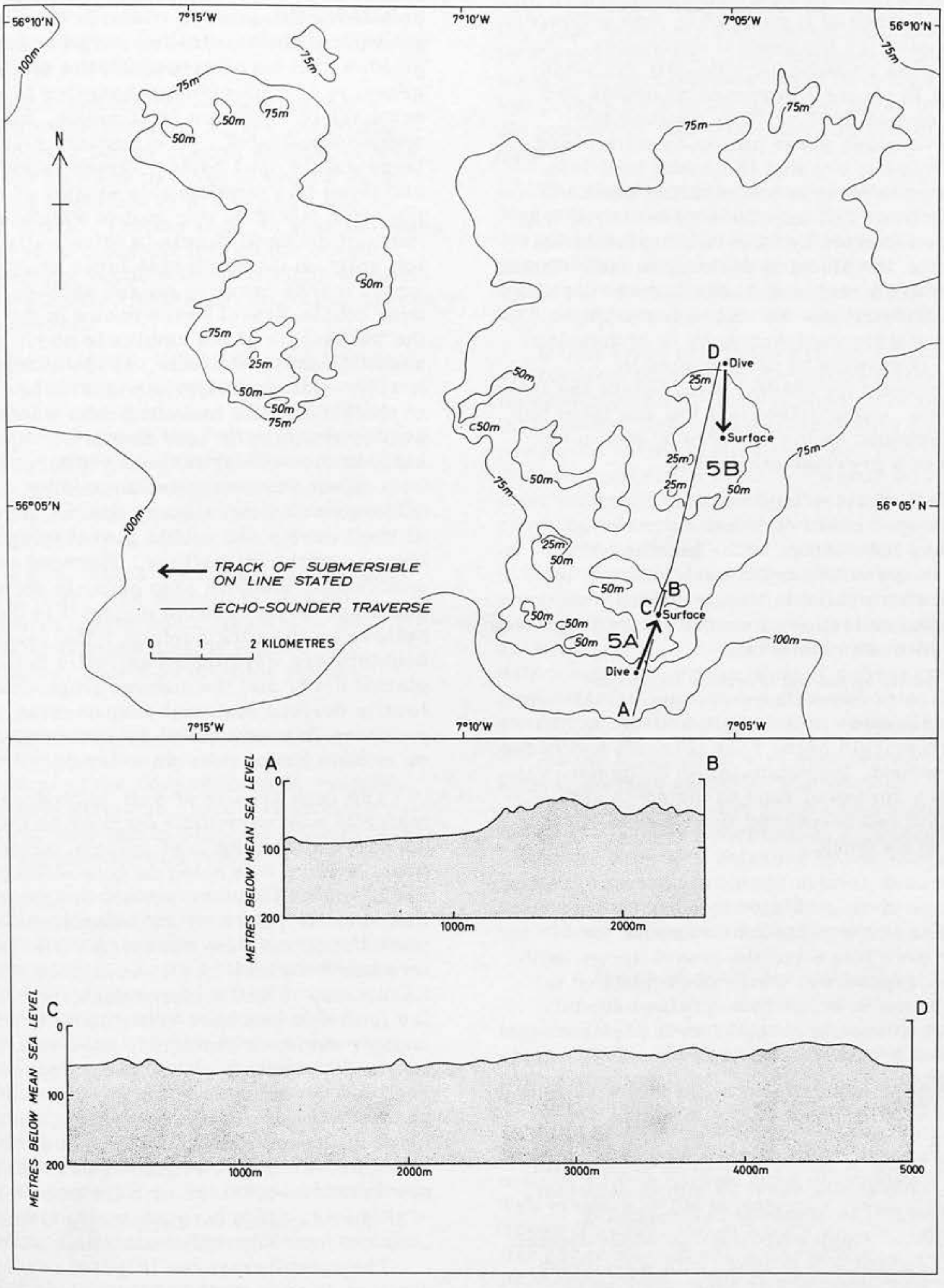



Fig. 10. Blackstones Bank. Traverses 70/5A and 5B. Location map and echo sounder sections.

Detailed geophysical survey subsequent to the dives indicates that the rock banks are the eroded remains of a larger intrusive complex (much of it covered by thin sediments,) which underlies the general shoal area. Both of the banks examined are heavily glaciated; there is in places a surrounding pebble and cobble spread at 60 to 70 m, backed by angular-boulder scree and steep cliffs; and the indications are that the banks have lain near to wave level at some period since deglaciation. The angular-boulder scree may have been derived by wave action, subaerial erosion or ice plucking working on their flanks; the tops are rounded and have been swept clean of glacial detritus. As elsewhere around Scottish coasts the topography is of complex origin; it appears to have existed in approximately its present form before the latest glaciation, and a subsequent low sea level has only sharpened up the features of what must have been a previous strand line.

Excellent video tape and photographic records were obtained in conditions of good visibility, but damage to the handling arm during the previous day's work left only the torpedo claw available as a sampling tool, permitting collection of random loose fragments but not of in situ material.

### Cobble Spread and Glaciated Topography on South Side of Blackstones Bank (70/5A)

The traverse was designed to ascend the southern margin of the bank (Fig. 10) and cross a rock mound, the submersible being put down on a spread of sand to the south side of the mound and recovered from a sand filled hollow to its north.

The rock area is 800 m wide where crossed; it is bounded on each side by a cliff with a zone of boulder scree at its foot. Around the boulder area lies a cobble-gravel apron, with low rock exposures, which is overlapped to south and north by medium-grained sand. A hollow within the cobble-gravel area contains ripple marked coarse shell sand.

The sand to north and south was not sampled; its edge was at a depth of 75 m on the south side and 52 m on the north. In each case it appears to be of uniform medium grain, with rare bivalve shells about 20 mm in diameter; on the south it is disposed in bifurcating symmetrical ripples broken into whale-backed segments about 0. 5 m long, with wavelength 200 mm and amplitude 75 mm, striking at N 150°; on the north side no clear ripples are visible but there is an unorientated ridged undulation of low amplitude, possibly an interference pattern.

The sand feathers out abruptly against the cobble-gravel apron, estimated to be of the order of 100 m wide to the south of the rock exposure, and somewhat less to the north where low glaciated pavements protrude through it. Sparse sand is locally present in hollows between pebbles and in one area the sand was seen to be concentrated on the west side of the pebbles. At its outer edge to the south, the gravel is of well-sorted subangular to rounded material 10 to 30 mm in diameter, apparently semi-consolidated, but elsewhere material of large cobble and boulder-grade is incorporated and there is a considerable scatter of shell material, about 50 per cent of which is broken; much of the shell debris is thick walled. In a low gully on the north side large symmetrical ripple marks occur in coarse shell sand lying over cobble-gravel which shows in the troughs; the wavelength of the ripples is about 2 m, height about 200 mm and strike, where observed, is N 140°. The sand here appears to be entirely of shell material, including rare whole bivalve shells of 20 mm diameter. On both sides of the rock area, zones of large boulders, with angular material predominating, are banked at the foot of steep slopes, with an admixture of shell debris and cobble gravel lying in the bottoms of the interstices. Rounded and subrounded boulders also occur in these zones, and a scatter of rounded material is found in hollows on the rock surface. The rounded boulders are interpreted as relict far-travelled glacial drift, and the angular fragments as locally derived material concentrated, and in part torn from the solid, by subaerial erosion or marine action near wave level.

The rock area is of well-jointed massive material with very little detritus on its surface. An outward-sloping joint system, striking at about N 120°, was noted on both sides of the area, and a prominent set of vertical joints was seen to trend at N 25°; numerous other joint directions were observed. The joints trending N 25° are locally excavated into fissures up to half a metre deep, and elsewhere the joint systems have controlled broken, angular surfaces which may have been formed by glacial plucking. The upper slopes of the rock outcrop are gently undulating with well-rounded massive knolls protruding upwards; much of the area shows bare rock surfaces of this type, which are regarded as glaciated pavements swept clean by wave action.

### Rock Exposures and Ripple-Marked Sediments on North Side of Blackstones Bank (70/5B)

The second traverse (Fig. 10) began at a depth of 69 m at the foot of the slope leading up to the northern edge of a rock bank.

The sediments on the sea floor to the north of the bank are poorly sorted sands with variable amounts of granule to pebble-grade shell and lithic debris. Isolated subangular to subrounded cobbles and boulders are not uncommon and for a short distance poorly defined ripple marks were observed. These have an amplitude and wavelength of about 60 mm and 200 mm respectively; their broad symmetrical crests trend at N 150°; pebbles and cobbles occupy the troughs, indicating that the ripples are crossing a cobble spread.

Up-slope towards the north edge of the bank, sediments become coarser and in one area a group of larger ripples occurs. These are similar in trend to those in deeper water but have an amplitude of 0. 5 m and a wavelength of 2. 0 m. Coarse sand to granule-grade lithic and shell material lies on the crests; the presence of cobbles in the troughs suggests that here also the ripples are migrating across a cobble spread.

The gravel-grade lithic material on this part of the traverse is predominantly angular or subangular and increases southwards in size and proportion to the foot of a scree slope. Two distinct sizes of material occur, cobbles and large pebbles, heavily encrusted with epifauna, and black granules and small pebbles, with no epifauna.

The scree, which contains boulders up to 300 mm across, lies beneath the lowest of a series of ledges and crags which the submersible climbed until it reached the uneven plateau shown on the echo sounder trace.

The traverse then led across gullies and rock platforms at the top of the bank. The general form of the rock outcrop is rounded and obviously glaciated, with a continuous layer of epifauna and in places a thick growth of kelp. No jointing was seen.

Sediments in hollows and gullies, contrasting with that in similar situations on Stanton Banks, contain a high proportion of lithic material. Some of the gullies have only rounded cobbles and boulders with small patches of poorly sorted sand and gravel; in others, cobbles and boulders on the edge of the gullies grade into finer material in the middle. In one gully, ripples 0. 75 m in height and 4 m in wavelength have been formed in predominantly pebble-grade sediment; their crests are rounded and they trend north-south, perpendicular to the steep side of the gully on which they abut. Cobbles, forming an underlying platform, appear in the troughs.

## CANNA RIDGE

Two dives were made on the flanks of the Canna Ridge, a shoal area of Tertiary basalts which extends 29 km south-westwards from the Island of Canna (Figs 1 and 11). Each of the dives, the first to the west and the second to the east of the ridge, was designed to climb onto the ridge from the flanking hollows occupied by recent sediments lying on stratified rocks of presumed Mesozoic age.

The 1968 geophysical work, in conjunction with Admiralty bathymetric data, delineates the ridge precisely and shows that it is bounded by steep slopes with rock exposures, and that the presumed Mesozoic areas have a generally low profile with much sediment cover but the possibility that this is locally thin or absent.

The objects were to check whether or not Mesozoic rocks are outcropping, to examine the topography of the Canna Ridge with its surrounding slopes and deeper water areas, and to observe variations in the type of sediment both on the shoal and in the surrounding hollows.

It was found that there are no indications of Mesozoic outcrop in the deeper water, where there is a uniform cover of mud or sandy mud; this appears to be thin in places with boulders, presumed to be erratics, below. The finer sediment passes gradually upwards into a muddy sand with scattered shell debris and, as the escarpment is approached, lithic fragments up to cobble-grade. The ridge itself has precipitous sides and although the top is encumbered with angular debris, probably of local origin, there are many exposed glaciated rock surfaces. Coarse, poorly sorted sediments with a high proportion of shell debris are trapped in hollows on top of the ridge. Large sand ripples were observed in one hollow.

As the handling arm of Pisces was out of action, no rock sampling was possible but a detailed photographic record was made. When the final dive was concluded at a depth of 40 m, a marker buoy was released by the submersible and two Scuba divers were able to obtain solid rock samples from the eastern edge of the ridge; as expected these were of basalt.

### Western Scarp of Canna Ridge (70/6A)

The submersible descended to a mud plain at a depth of 122 m (Fig. 11) on a gentle eastward rise which gradually increased, the mud giving way imperceptibly to sandy mud. At 103 m cobbles were encountered and cobble spreads with shell sand were observed to increase eastwards as the slope steepened, until at 82 m a narrow zone of boulder scree was crossed at the bottom of a 20-m cliff. Above the cliff, the submersible traversed a flat rocky plateau encumbered with angular rock-fragments. This plateau constitutes a spur jutting south-west from the main Canna Ridge.

The edge of the mud plain was crossed for a distance of approximately half a kilometre. The sea floor consists of brownish grey mud pock-marked with about 100 burrows to the square metre; most are some 20 mm in diameter, but there are large Nephrops craters distributed at about one to the square

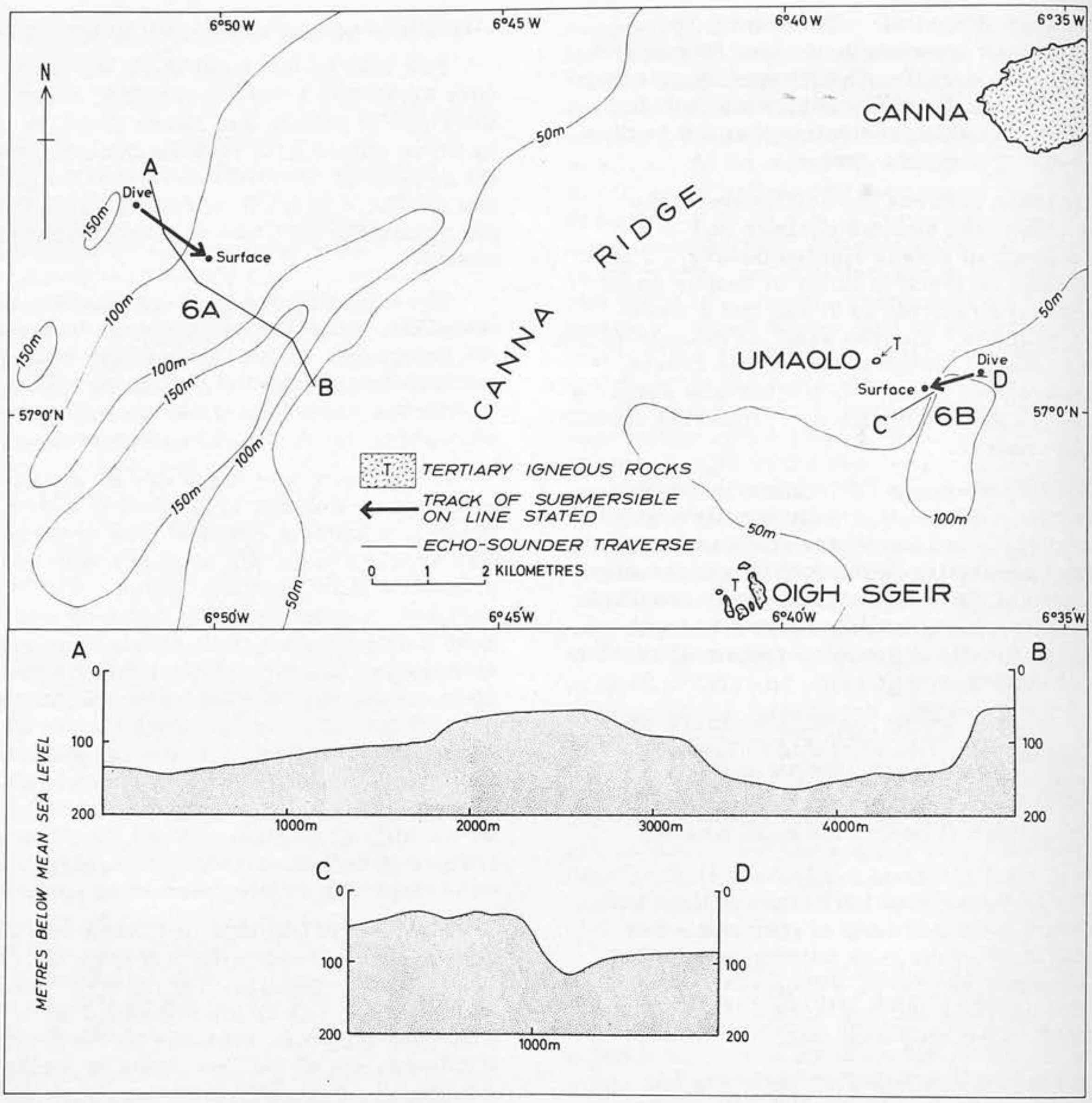



Fig. 11. Canna Ridge. Traverses 70/6A and 6B. Location map and echo sounder sections.

metre. Between the burrows the mud is smooth and textureless, and material thrown out is the same as that at the surface. Sea pens of two types occur, one about a metre long and the other about 150 mm, approximately one of each type every two square metres. Isolated subrounded boulders protrude from the mud and occasionally the skids of the submersible, sinking slightly into the surface, touched the tops of others; rare large sea anemones appeared to be seated on the tops of such concealed boulders. There is no evidence whether the boulders, up to a metre across, represent the top of underlying till or whether they are emplaced within the sediment, but the mud may be deceptively thin.

The mud gradually passes upwards into brownish grey sandy mud with rare shelly flecks and a few conical 'volcano'-like protrusions about 50 mm high. At a depth of 89 m a small crinoid field was crossed; above this, cobbles are commonly present, either scattered in the sediment or forming cobble-gravel spreads. Here the sea floor shows rapid lateral variation between extremes of mud with burrows, and cobble-gravel with scattered boulders; there is a continuing gradual upward increase of slope with no topographic expression of these variations. Calcareous flecks become more abundant upwards, so that the sediment passes gradually into a muddy shell sand in which some of the shell fragments are up to 2 mm across. In places a dusting of dark coloured mud is draped over the surface of the deposit.

In the stony patches, which become larger as the slope is ascended, the cobbles are predominantly angular and the boulders rounded, but rounded fragments of all grades occur; there is a widespread superficial scatter of shell sand. Although much of the material shows no sorting, on the higher parts of the slope there are large patches where uniform angular gravel-fragments about 20 mm in diameter are worked in with shell sand. The benthos on the stony patches includes regular echinoids and small clams. Trails about 50 mm wide are made by a hump-shaped burrower which moves about a centimetre below the surface in the areas of mixed gravel and shell sand, pushing the gravel fragments to one side.

The gravel is inferred to be water-graded material derived from the ill-sorted morainic detritus of the type which constitutes the remainder of the stony spreads and which has been partly removed from higher areas above the cliff. Present day activity is, however, confined to the lifting and transport, by wave action and tidal currents respectively, of the thin superficial dusting of mud, its incorporation into the deposits by burrowers, the mixing of shell debris into the mud and unconsolidated gravel by burrowers, and presumably the periodical movement of fragmental shell material from higher levels by wave action. No current structures were observed.

The NW-facing basalt escarpment is skirted by a narrow zone of angular-boulder scree, and has low vertical cliffs of well-jointed rock interspersed with ledges and steep slopes of muddy boulder scree and rock breaking along angular fractures; the overall slope is about 45°. The cliff has been glacially plucked rather than smoothed, and the presence of boulders balanced on ledges suggests little marine erosion since deglaciation.

There is an abrupt lip at the top of the cliff at 45 m as it gives way eastwards to a rocky plateau on which angular blocks, mostly of cobble and small boulder-grade, lap round low rock pavements. The rock exposures, which constitute about 25 per cent of the surface, vary from smooth to angular and locally show knobbly protrusions up to 200 mm high. There are many well-developed joints; one prominent set strikes at N 120°. It was not possible to sample the in situ rock, but the angular nature of the loose blocks suggests a local derivation; one of these was collected and proved, as expected, to be of basic igneous material. There is locally a groundmass of ill-sorted gravel, and small patches of shell sand with prominent black flecks occur in some of the interstices between the blocks. Large benthonic fauna is scarce and the blockfield has a desolate appearance.

The submersible proceeded with considerable difficulty across the blockfield, being unable to skid across the surface and unable to lift off without being carried sideways by a strong current from the south.

The plateau is inferred to be a glaciated pavement with a cover of till well-winnowed by wave action at a time when sea level was lower than at present, but not sufficiently low for all of the coarse fragmental material to be removed.

### Eastern Scarp of Canna Ridge (70/6B)

A broad trough runs beneath the eastern scarp of the Canna Ridge at the dive site, and to the east of this the sea bed rises to a flat area (Fig. 11). The submersible dived in 79 m of water onto the eastern edge of the trough and travelled first south-westwards with the current into the trough, then north-westwards up the escarpment.

The sediment flooring the trough is a fine muddy sand or sandy mud; it is pitted with Nephrops burrows, and isolated sea pens occur. Visibility in the trough was less than 2 m but improved as the dive progressed. As the sea bed slopes upwards shell debris becomes increasingly common and, just below the scarp, lithic fragments up to 100 mm in diameter lie in the sediment and grade into a scree slope which also contains angular to subrounded cobbles and boulders. There is a thin film of mud on all surfaces.

Above the scree slope the scarp rises in a series of vertical faces and ledges; some of the ledges are wide enough to hold small patches of scree, and a thin film of mud covers all except the steepest faces.

The eastern side of the Canna Ridge has a typical glaciated surface similar to that observed on the western side but with considerably less detritus. Boulders and cobbles lie scattered on smoothed rock surfaces, and hollows and gullies are filled with a coarse very poorly sorted muddy sediment containing variable amounts of shell debris and lithic fragments up to cobble-grade.

The submersible crossed the edge of the plateau at a point where it is bounded by a high rock rim (not seen on the echo sounder section, Fig. 11, C-D), crossed a broad depression in the rock surface and climbed some way up the other side before returning to the edge of the scarp to rendezvous with divers who were able to collect a sample of basalt from the solid.

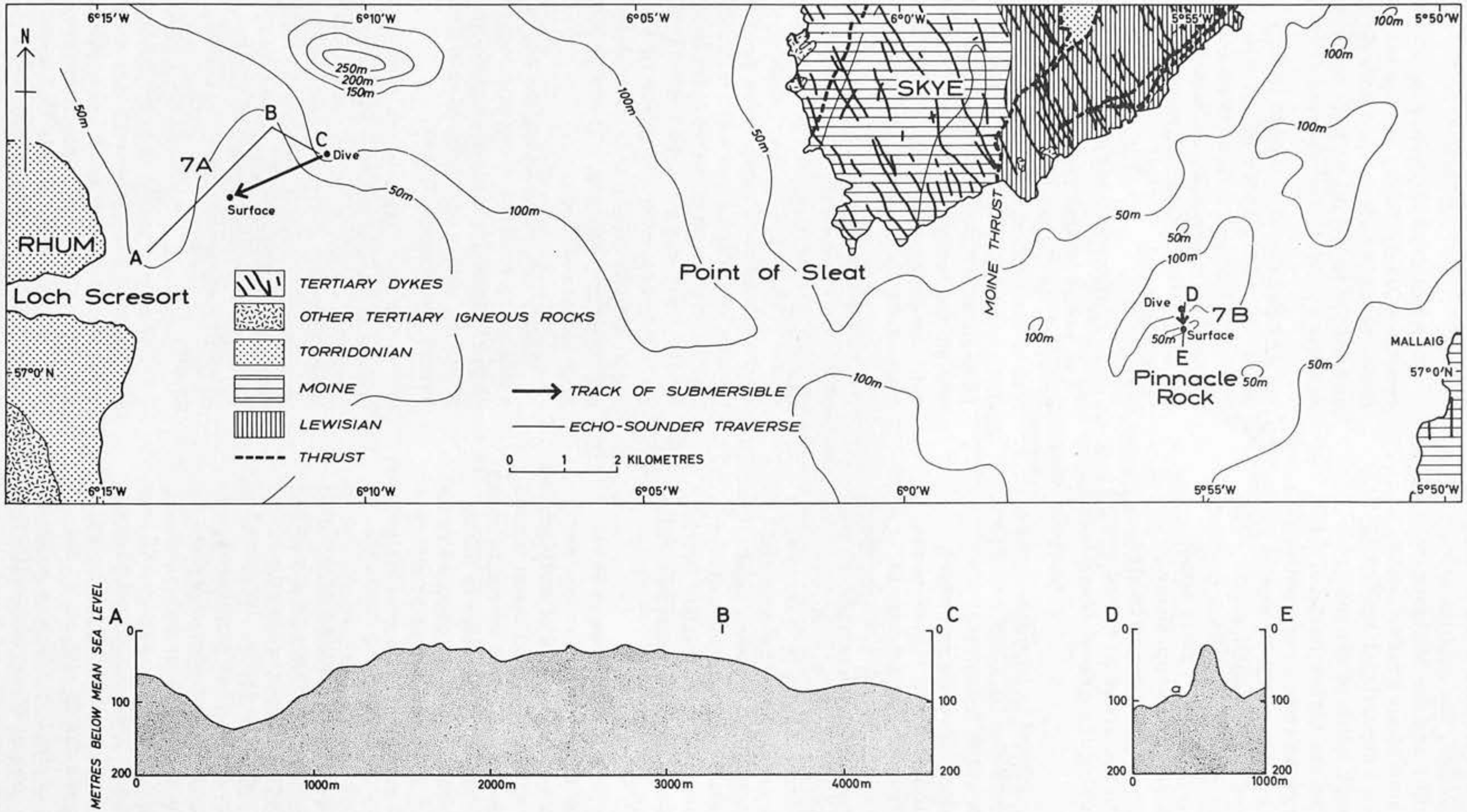



Fig. 12. South-east Skye and Rhum. Traverses 70/7A and 7B. Location map and echo sounder sections.

## SOUTHERN SKYE AND RHUM AREA

Two dives were made off the Sleat peninsula of southern Skye. The first traversed a shoal lying between the peninsula and the island of Rhum and had the objects of investigating recent sediments in an area close into the islands, and identifying the solid rocks of the shoal close to the postulated southern extension of the Camasunary Fault, which causes Mesozoic rocks to the east to abut against Torridonian to the west (Richey and others, 1961, p. 24). No clear evidence of the fault position can be seen on sparker records but the trench between the shoal and the coast of Rhum was regarded as a possible site (Fig. 12, A-B). If the fault lies in this trench the shoal would be expected to consist of Mesozoic rocks.

The attitude of the massive, dipping strata observed was, however, identical to that of the Torridonian sandstones of north-east Rhum, and it has been concluded that the shoal also is formed of Torridonian strata; the inference is that the Camasunary Fault probably lies farther east. Fine-grained sediments floor the deeper water to the north-east of the shoal and become coarser and more poorly sorted as the water shallows westwards; close to the shoal they can be seen covering relict glacial fragments.

The second dive had the dual purpose of examining the floor of the Sound of Sleat, a deep glaciated channel with strong surface tidal currents, and a steep rock ridge which rises abruptly from it (Fig. 12). Geophysical evidence indicates that there is a magnetic anomaly associated with the ridge, but this topographic feature trends ENE, almost at right angles to the direction of the Tertiary dyke swarm.

The Sound, in spite of the considerable local currents, was found to be floored by fine muddy sediments. No scree was seen beneath the ridge, which rises abruptly out of the mud plain and is made of massive structureless material most likely to be a plug or similar intrusion of Tertiary basic igneous rock.

Because of the handling arm being out of action, sampling was confined to the retrieval of one loose block at each locality with the torpedo claw. During the first dive the handling arm suffered further damage as a result of another collision with a rock face, which put it permanently out of action for the remainder of the cruise.

### Torridonian Topography off North-East Rhum (70/7A)

The traverse commenced at 110 m on a mud plain and proceeded up a steepening slope to an irregular plateau, with rock scarp and dip slopes, lying between 27 and 70 m.

The mud plain, which at the initial dive location slopes up to the west at about 3°, consists of greyish brown silty mud with burrows of 10 to 20 mm diameter distributed at about $250/m^2$, and with scattered larger Nephrops holes. Locally larger burrows have collapsed to form low irregularities on the sea floor. Conical sediment-mounds some 50 mm high occur, with a small crater and vertical burrow at the top. Two types of sea pen are present, one slender and up to 1.0 m tall, the other fern-like and about 150 mm tall.

Close to the dive site the sea floor slopes progressively more steeply up to the west, and there is passage first into a shelly, sandy mud and then into similar material with patchily distributed cobbles and a few boulders up to 1.0 m in diameter. The maximum slope is approximately 35° near to the base of the lowest rock exposure at a depth of 35 m. A scree slope of subrounded boulders and shelly, sandy mud lies immediately below this cliff. An abundance of dead turritellid shells is a notable feature of the slope, especially in the area close below the boulder scree; clams were also observed.

The lowest cliff has a strike of N 160°; it comprises a series of massive rounded steps totalling 8 m high and leading up to a jointed rock payement at 27 m. This is the most easterly of three comparable cliffs which were climbed in the course of the traverse. The cliffs are inferred to be Torridonian scarps, and between them lie dip slopes covered by cobbles and boulders, and also broad hollows of the order of 10 m deep which are mostly occupied by sediments but which include low, rounded, eastward-facing rock steps. Locally, vague indications of massive bedding are to be seen, giving the overall impression of strata dipping 30° to 40° in a direction of N 250°. This is consistent with the attitude of the Torridonian sandstone of Rhum. Glaciation has produced a roche moutonée appearance suggesting ice movement from the east. In the floors of the hollows, cobble aprons pass downward to muddy sand with much shell detritus on both dip and scarp slopes; in deeper parts the mud is less shelly, and has sea pens and many burrows.

At one locality two small patches of sand waves in coarse shelly sand were observed at 25 m, close to the base of a rock wall; the waves were of amplitude 100 mm and wavelength 0.5 to 0.75 m, some with bifurcating crests.

### Pinnacle Rock, Sound of Sleat (70/7B)

The ridge of Pinnacle Rock lies at the south-west entrance to the Sound of Sleat (Fig. 12). To its north the sea floor is overdeepened,

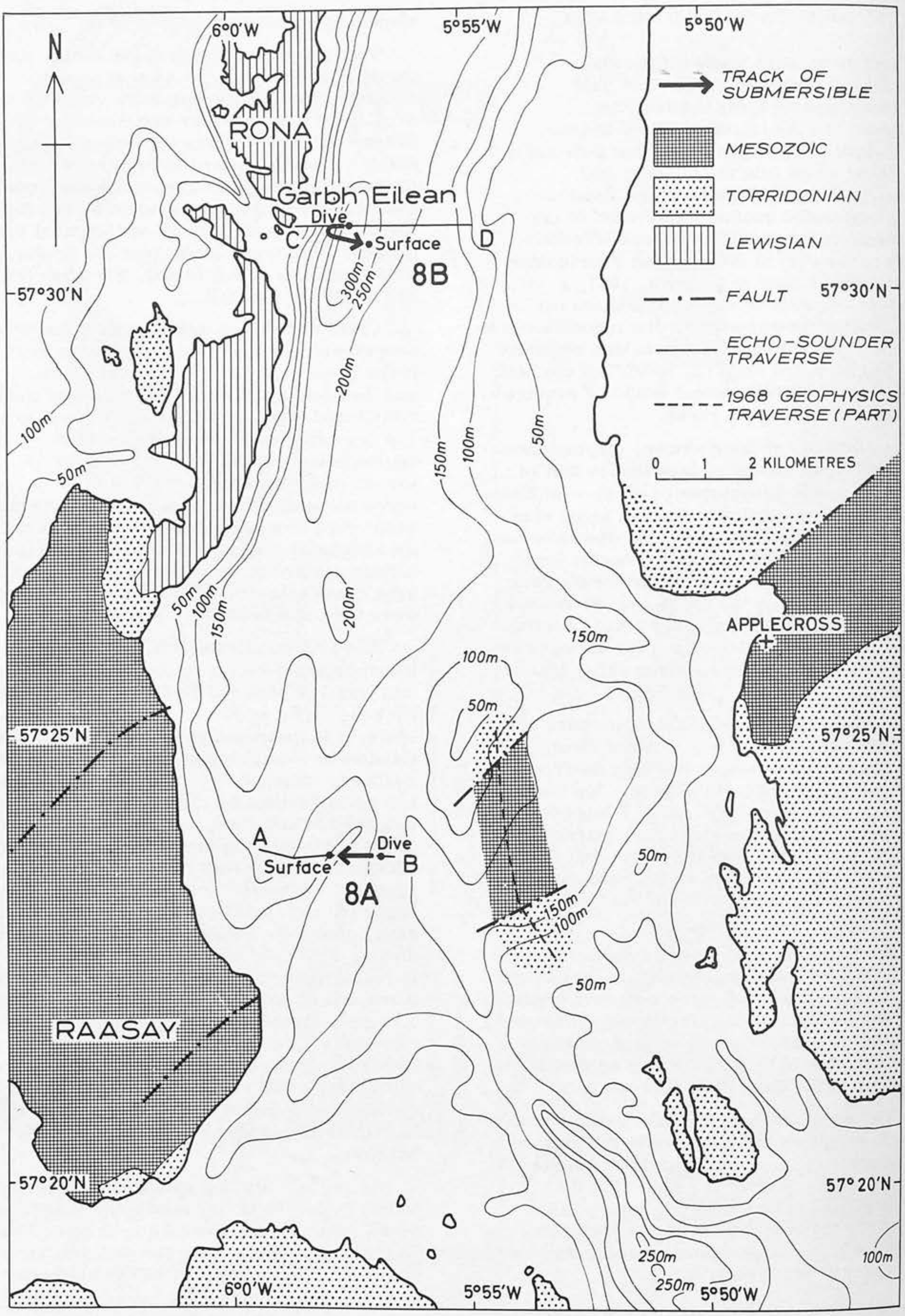



Fig. 13. Inner Sound. Traverses 70/8A and 8B. Location map.

presumably by ice bearing on the ridge as it travelled south-west along the Sound. The submersible started its traverse in the overdeepened area and travelled southwards up onto the Rock.

Visibility at the start of the dive was no more than 2 m, due to fine sediment being carried in suspension by a south-westerly current down the Sound. The sea floor was similar to that observed elsewhere in deep hollows on the shelf, comprising fine muddy sand or sandy mud, pitted with Nephrops burrows and with isolated sea pens.

About 150 m to the south of the dive site, the sea floor begins to slope up to a crag about 3 m high which lies at the edge of the ledge shown at a on the echo sounder section D-E, Fig. 12. Farther south again the sediment surface on this ledge slopes up with increasing gradient to the foot of a 60-m cliff. The fine-grained sediment observed at the start of the dive persists to the foot of the cliff; some shell debris lies on the slope below the cliff but no scree is visible.

The cliff itself is almost vertical but there are a number of small mud-covered ledges; the rise begins to level off at a depth of 30 m and the dive ended on a rugged rock surface a short distance above the top edge of the cliff. The rock itself is homogeneous and without schistosity or jointing; a fragment similar in aspect to the solid rock was picked up by the torpedo claw from the top of the ridge and was later found to be of dolerite. It is inferred that the ridge is formed by an irregular intrusive body similar to those on the Sleat peninsula.

Poorly sorted sediments, resembling those on the Canna ridge, lie in hollows on the rock surface. They contain a low percentage of mud and a high percentage of granule and pebble-grade material including abundant bivalve fragments. Many living clams were found on this sediment and regular echinoids were observed on most rock surfaces.

## INNER SOUND

Two dives were carried out in the Inner Sound, a semi-enclosed sea area between the complex Rona-Raasay ridge and the Applecross peninsula of the mainland (Fig. 13). They were designed partly to examine the geomorphology and sedimentary environment of this deeply trenched area close to the Scottish landmass, and partly to attempt to obtain information about the solid geology of two escarpments.

The general direction of ice movement in the Inner Sound area was from south to north (Robinson, 1949, p. 23), and glacial erosion has been at least partly responsible for the formation of deep trenches orientated in this direction. In the north there is an asymmetric depression which reaches a depth of 323 m, the deepest recorded on the British continental shelf; in the central part glacial erosion appears responsible for a gap cut in the prominent transverse ridge running NE-SW from Torridonian rocks on the headland north of Applecross to Jurassic rocks forming the south-east corner of Raasay. Both the deep trench in the north and the south-east flank of the central transverse ridge are fault-controlled; the dives were planned to examine these two areas.

A geophysical traverse in 1968 (Fig. 13) crossed the Inner Sound but not the sites of the two dives. It did, however, pass over the eastern part of the central transverse ridge, indicating that the ridge is there built of partly exposed magnetically flat rocks with poor indications of northerly dips, of probable Torridonian age. The traverse also indicated better stratified northward dipping strata in the area south of the line of the Applecross Fault, to be compared with the Mesozoic rocks at Applecross; these strata were shown to be covered by drift up to 55 m thick.

The dive on the transverse ridge proved a markedly stepped topography on massive bedded and jointed sandstone, almost certainly Torridonian in age; in the north, in the deep off Rona, a conglomeratic or brecciated rock of presumed Lewisian age was seen on the west side of the deep, but on the east side no exposures were found in the time available. A feature of both dives in this sheltered coastal area was the very muddy nature of much of the bottom, mud being plastered over every ledge, and soft tenacious mud adhering even to very steep rock faces in the deep trench. The transverse ridge was found to carry a considerable cover of ill-sorted boulder and cobble debris. presumably ice-transported. Some of the boulders in deeper water were precariously balanced on narrow ledges. There were no indications of any former low sea level.

Work was confined to observation and photography as the handling arm was out of action, but a loose angular boulder was collected, by use of the torpedo claw, on the transverse ridge; it proved to comprise red quartzite of inferred Torridonian age. Minimum visibility with the floodlights on was 3 m in mud areas, except when sediment was disturbed by the submersible.

### Torridonian Topography East of Raasay (70/8A)

The submersible descended onto a typical mud plain at 158 m, near the top of a gentle south-east slope extending down to nearly 200 m (Figs. 13 and 14). Only about 100 m of the mud plain were traversed; in this area burrows of about 20 mm diameter are

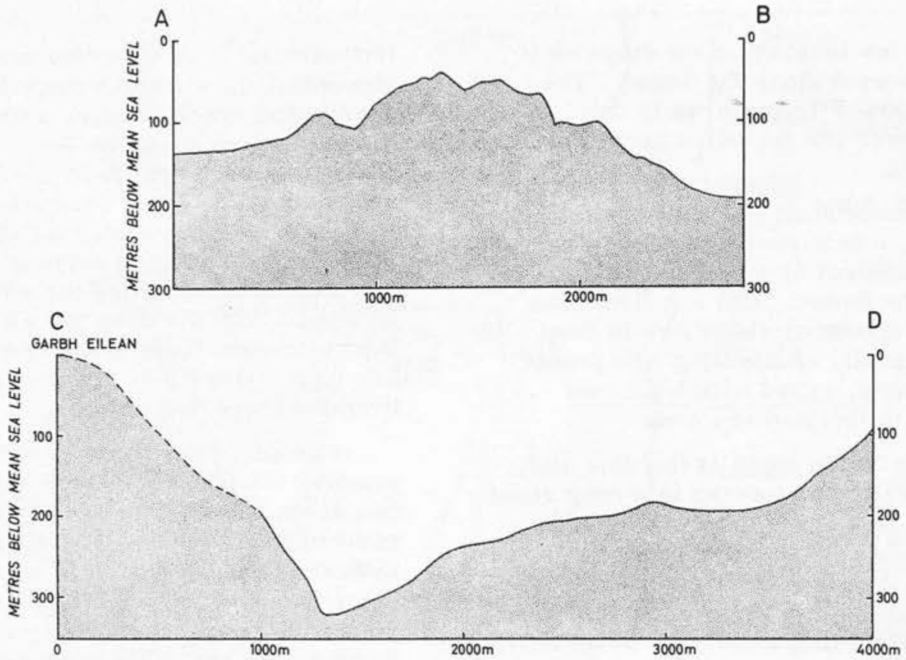



Fig. 14. Inner Sound. Traverses 70/8A and 8B. Echo sounder sections.

distributed at about $30/m^2$. Large rounded boulders occur near the edge of the plain, where the mud slopes perceptibly upwards as it butts against the foot of a steep rocky crag.

The traverse led up a cliff from 140 to 100 m to an undulating shoulder, some 150 m wide at around 100 m depth, with rock exposures, boulder beds and muddy hollows, then up a series of rock steps and muddy scree slopes to a similar undulating area, from 65 to 40 m depth, at the top of the central transverse ridge. The dive was terminated at the edge of a steep slope down to deeper water on the north-west side of the ridge.

The cliff between 140 and 100 m strikes nearly north-south and is part of the main glacial channel of the Inner Sound where it cuts through the central transverse ridge. The lower half has an average inclination of 50°, with crags and steep mud-covered slopes. Above this is a vertical cliff about 15 m high, with a smoothly undulating surface and slight overhangs, but also considerable mud scatter on local steep ledges. In the top 3 m the slope decreases slightly and numbers of subangular boulders up to half a metre in diameter are balanced on narrow ledges. The rock is jointed, one prominent set of joints striking at N 120° and dipping northwards at 75°, and there are local indications of massive bedding dipping at about 10° to the west (Plate 7b).

The 150-m wide undulating shoulder above this cliff is characterised by vertical crags about 2 m high, most facing to the east but some to the west. Between the crags are spreads of mud which rises into suspension less readily than that in deeper water, and which includes rare shell fragments up to 5 mm in diameter; large Nephrops burrows are distributed at about one every 2 $m^2$ but smaller burrows are absent. There is a considerable scatter of angular, subangular and a few rounded cobbles and boulders up to half a metre across, both in the mud spreads and banked against the crags. Local indications of near-horizontal bedding are to be seen in the solid rock; at one place individual beds ranged from 200 mm to a metre thick, at another a 10° dip to the south was observed. The vertical crags appear to be formed by joint planes, one well-defined set striking at N 120°.

Westwards of the undulating shoulder, a stepped slope leads up from 100 m to 65 m. The aspect of the rock crags remains the same, but steep upward slopes between them include a variable high proportion of shell detritus mixed with unsorted mud and angular rock fragments. The visible calcareous material is well broken, and locally reaches an estimated 25 per cent of the volume of the deposit.

The undulating area at the top of the bank includes rounded knolls of which the highest seen rises to 45 m. Massive horizontal bedding is well displayed and this, together with intersecting joints, trending N 120° and N 20°, produces rectangular recesses and buttresses. In one location there is an indication of SSE-NNW glacial gouging. Amongst the rock exposures are slopes of ill-sorted shell sand; there are numerous rounded to angular boulders and a proportion of angular gravel and cobble-sized material. A boulder collected in the torpedo claw proved to be a hard compact red sandstone of inferred Torridonian age.

### Deep Trench East of Rona (70/8B)

This dive was planned to examine the sediments on the floor of the exceptionally deep trench to the south-east of the Isle of Rona, the steep eastern wall of the Rona-Raasay ridge, and the more gently inclined eastern side of the trench where undulous topography may be due to solid rock exposures (Figs. 13 and 14). Progress was hampered throughout the dive by the skids of the submersible sinking into the soft sediment.

At the descent position at 307 m, the level floor of the trench consists of silty mud, greyish brown on the surface and brownish grey beneath, both containing a small amount of fine shell material. Numerous burrows are present, including those of Nephrops, and diameters range up to 150 mm with an average of 30 mm; density is approximately $25/m^2$. Scattered sea pens occur.

To the west an upward slope sets in and increases progressively, reaching some 60° at 282 m where the torpedo claw struck a hard substratum beneath the superficial sediment. A boulder and a small mud-covered exposure, both unidentified, were seen on the steepening, sub-vertical slope above this depth. At 192 m there is a small exposure of what appeared to be a brecciated or conglomeratic rock, but the exposure was seen only intermittently as the movement of the submersible, hovering against the cliff, continuously raised clouds of sediment. Little marine growth was apparent on the rock and it is likely that the mud covering had been removed by the motion of the submersible.

The sediment on the cliff is extensively burrowed by both Nephrops and smaller animals, there being locally an adequate thickness of mud even for relatively large burrows. The only notable change in the sediment on the slope relative to that in the trench is the presence of somewhat larger shell fragments, very sparsely distributed.

At 190 m the submersible turned through 180° and travelled east in mid-water to descend again to the central mud flat at 305 m depth. Eastward the sea bed was followed upwards to 259 m, rising in undulations with slopes between 5° and 40°. Around 274 m brittle stars and a limited number of echinoids and starfish occur, but no rock exposures were seen.

## HAWES BANK AREA

Hawes Bank is a major shoal north-west of Coll (Figs. 1 and 15). It is bounded on its north side by an E-W glaciated trench and the object of the first dive was to investigate the floor and southern wall of this trench and the edge of the bank. To the north of the trench there is no equivalent large shoal but several smaller banks rise above the 50 m contour; on the second dive, investigations were carried out on the flank of the largest of these.

Both traverses followed the pattern of earlier trench to bank traverses. As Hawes Bank is approached, the fine muddy sediments of the trench give way to coarser, more poorly sorted material lying at the base of a series of cliffs and ledges leading up onto the bank. The bank itself has a glaciated surface cut by gullies filled with ripple-marked shell sand. The presence of massive bedding scarps in places suggest that the rock may be a Torridonian sandstone, a deduction consistent with 1968 Sparker and Magnetometer data. Visibility throughout was good.

The short second traverse also passed from mud to gravelly sediment and then to massive-bedded rock inferred to be of Torridonian age. This dive was carried out in poor visibility, and had to be terminated prematurely because of a loss of battery power.

### Glaciated ?Torridonian Sandstone of Hawes Bank (70/9A)

The submersible dived to 156 m to the bottom of the trench north of Hawes Bank and travelled southwards onto the bank (Fig. 15).

The sea floor sediment north of the bank is similar to that widespread in deep water areas around the Hebrides. Fine-grained material, apparently fine sandy mud, is pitted with Nephrops burrows and scattered with isolated sea pens; live bivalves also occur. As the gradient steepens upwards the proportion of sand-grade material in the sediment increases and the surface becomes strewn with shell and lithic debris.

The sediment abuts directly against a vertical rock face, and the bank rises in a series of steep faces, ledges and small scree slopes. Cobbles and boulders in the scree (Plate 8a) are subangular to subrounded and in many places lie below a thin blanket of fine sediment with scattered shell fragments.

The rise levels off at a depth of 38 m, passing into a smooth rock rim at the edge of the bank. On the bank a glaciated rock surface with isolated boulders is divided by numerous small crevices and depressions and by local deep, wide gullies several tens of metres across. The small

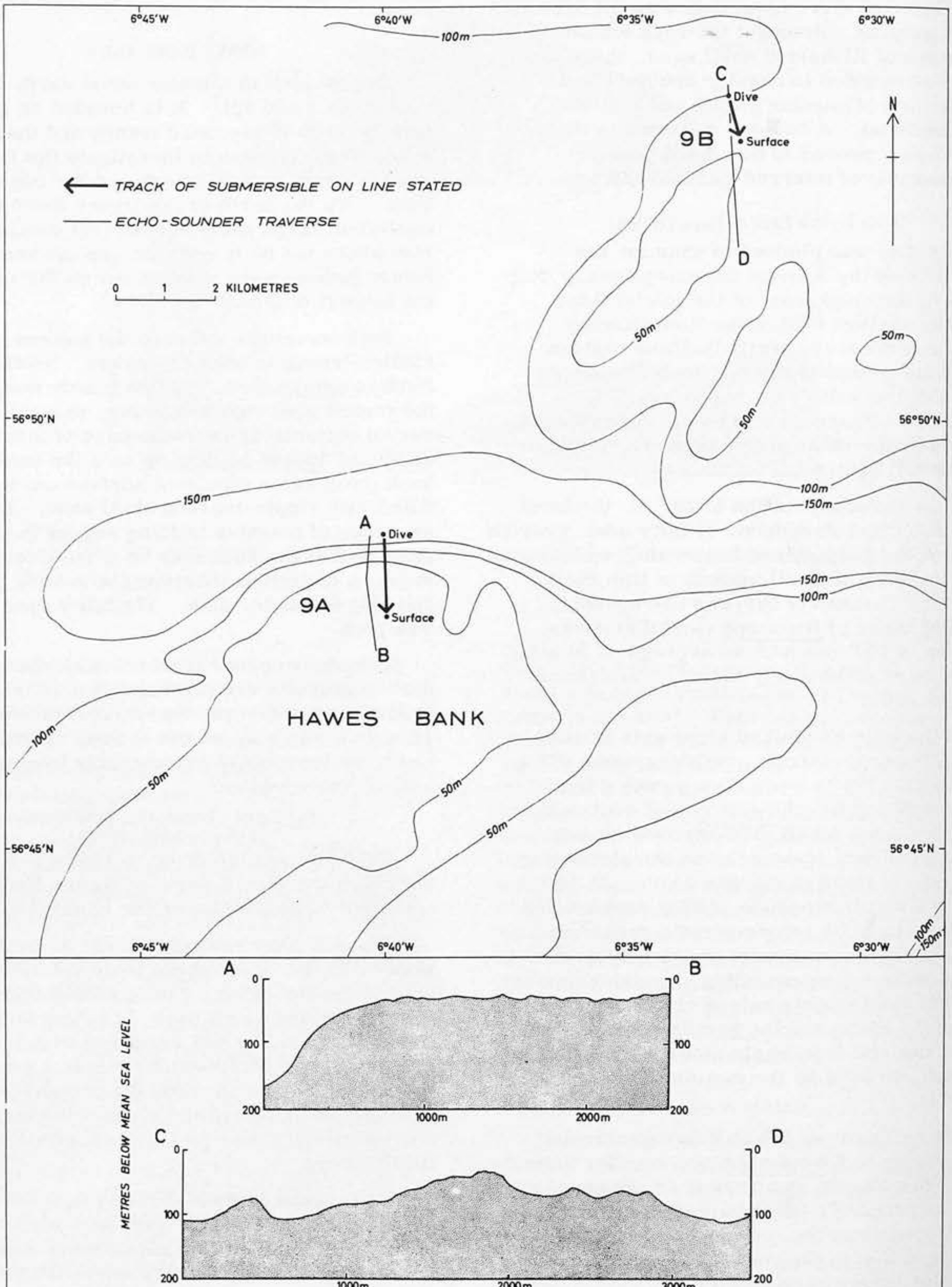



Fig. 15. Hawes Bank. Traverses 70/9A and 9B. Location map and echo sounder sections.

depressions contain cobbles and boulders up to 1.5 m diameter; in most the material is poorly sorted but in one hollow fairly uniform cobble-grade material was seen.

Three of the broader gullies were crossed; all are floored with coarse shell sand of generally even texture but with some dead bivalves and a proportion of granule and pebble-grade lithic material. The first gully encountered is bounded on the north by a crag about 3 m high; at the foot of this crag isolated boulders lie in the shell sand. As on other banks the sand is formed into ripples trending at right angles to the line of the cliff. The ripples are symmetrical and discontinuous, with a wavelength of 1·0 m and an amplitude of about 0·5 m. On the south side of the gully subangular and subrounded pebbles and cobbles gradually replace the shell sand, which appears to overlie them. Sediment in the other two gullies traversed is similar to that in the first.

Because of the ubiquitous cover of epifauna, no small-scale internal structures can be made out in the solid rocks. In general they are massive, but locally, apparent bedding planes can be seen dipping gently in a direction of N 120° with small strike scarps, somewhat less than half a metre high, at right angles.

### ?Torridonian Sandstone Outcrop North of Hawes Bank (70/9B)

The submersible dived to a depth of 100 m and crossed a minor peak shown at left of section C-D, Fig. 15), then proceeded part of the way up the side of a larger bank.

North of the minor peak is a level area of greyish brown sandy mud with subangular cobbles and scattered boulders up to 1·0 m. The cobbles, averaging 150 mm in diameter, occupy 40 per cent of the surface. The level area gives way towards the south to an upward slope reaching 20°, with an increasing cobble fraction. From 88 m to the top of the peak at 73 m, alternating patches of cobble-strewn sediment and smooth rock occur on the slope. A thin veneer of sandy mud and a profuse growth of cup-shaped sponges are found on the rock areas.

The south side of the minor peak differs markedly from the north, descending in a series of rock steps each about 2 to 4 m high, separated by relatively level areas of sandy mud, gravel, cobbles and boulders. The steps were not easily examined during the descent, but they are inferred to be individual bedding scarps of Torridonian strata; one exposure displayed possible bedding planes and jointing.

South of the minor peak lies a spread of mud at about 100 m. This gives way southwards to a narrow upward sloping apron of shelly, cobbly material abutting against boulder scree at the foot of a vertical rock wall 12 m high. The nature of this wall, which is not apparent on the echo sounder trace (section C-D, Fig. 15), could not be ascertained; it possibly represents a dyke.

Above the rock wall ill-sorted lithic fragments pass south to a sea floor predominantly of muddy shell sand. Three patches of ripples were observed, each about 10 m across and separated by about the same distance; one has waves with a wavelength of 1·0 to 1·5 m and amplitude 300 mm; the other two have wavelengths and amplitudes of 500 mm and 100 mm respectively. All the ripples are orientated in a SE-NW direction.

## AREA BETWEEN COLL AND MUCK

Two short dives on the last day of operations were designed to investigate an area in which samples of solid rock were required to settle ambiguities in the 1968 geophysical data. An IGS Harrison drill motor and core barrel fitted into the Pisces torpedo claw was available for experimental rock sampling (Plate 2b).

Both traverses crossed areas of exposed glaciated rock and on the first the drill recovered a core of red Torridonian sandstone. No core was recovered on the second dive but the presence of bedding scarps, which were also apparent on the echo sounder trace, suggests that this too was on Torridonian sandstone.

On both dives, scattered lithic detritus was found on rock surfaces and ill-sorted concentrations of the material in hollows, with angular blocks below escarpments. Pockets overlying shell sand have large ripple marks in shallower water.

### Torridonian Topography South-West of Muck (70/10A)

An echo sounder run prior to the first dive indicated a platform, with a somewhat irregular topography, lying between 50 and 80 m (Fig. 16, section A-B).

The descent position was on a flat spread of cobbles and small boulders adjacent to a suitable exposure for drilling, a smooth rock surface sloping at 15° towards the submersible. The torpedo claw was lowered until the drilling crown rested gently on the surface, and the drill was switched on. After seven minutes, when about 80 mm penetration had been achieved, the drill was switched off and the barrel withdrawn by moving the torpedo claw upwards. Two attempts to withdraw had to be made; the first was unsuccessful as the barrel jammed in the hole due to the arc movement of the claw. When the core was later extracted from the barrel on board ship it proved to be a red quartzite of presumed Torridonian age.

The remainder of the dive was a traverse

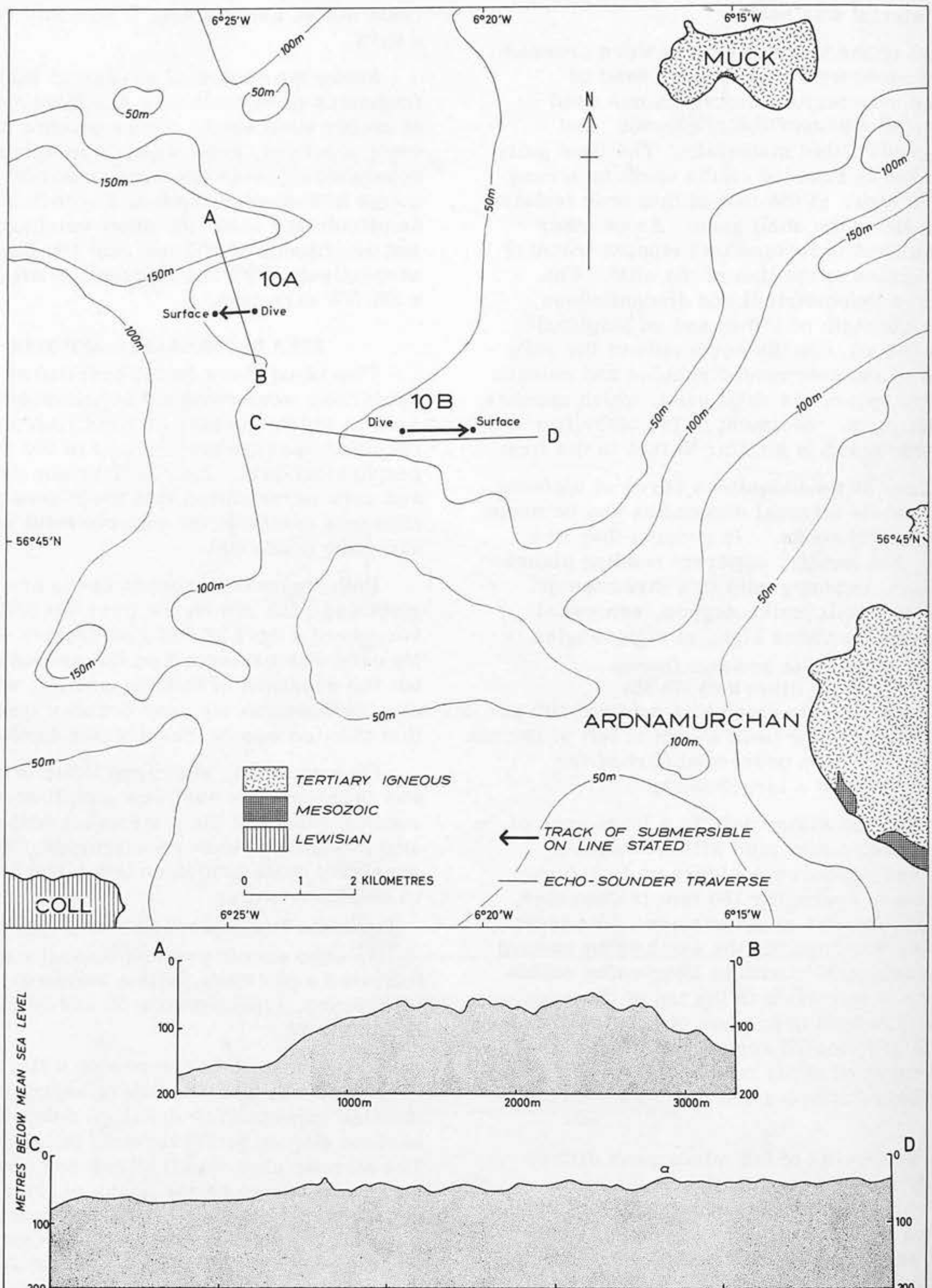



Fig. 16. Area between Coll and Muck. Traverses 70/10A and 10B. Location map and echo sounder sections.

across a shallow glaciated hollow cut into a Torridonian scarp-and-dip flat topography, with varied sediments resting on the bedding plane surfaces.

Rock exposures include smooth glaciated pavements, roches moutonnées, and sharp escarpments up to 2 m high, apparently dispersed at random. Massive bedding was clearly seen in many places, lying flat or with northerly dips of up to 10°. The strata are cut by joints, of which two well-defined sets run at N 20° and N 110°. Subangular to subrounded blocks, defined by these two joint directions and the bedding, were observed weathering out on some of the low escarpments.

Unconsolidated lithic material comprises rounded glacial erratics of all sizes, angular local detritus banked up against the escarpments, including blocks up to 2 m across, flat spreads of generally unsorted subrounded to subangular boulders, cobbles and gravel, and patches of fairly well sorted gravel of 20 to 30 mm diameter. None of this material appears to be in transit. The concentration of angular blocks below escarpments suggests the effects of a low sea level, but no cobble 'beach' is recognisable. The general aspect is of a glaciated surface on which detritus has been winnowed and roughly sorted in water shallower than at present.

Superimposed on the lithic debris are patches of shell sand, disposed as flat spreads in deeper water (80 m) and locally as larger ripples in shallower areas. A typical ripple-marked area at 70 m had ripples of 1·5 m wavelength and 200 mm amplitude striking at N 30°; the top of the underlying gravel locally shows in troughs, in which also are concentrated the larger shells including living and dead clams. The sand spreads in deeper water are of finer grained material, although they everywhere include at least 25 per cent of recognisable shell material; scattered burrows about 10 mm in diameter occur at a density of about $4/m^2$ and there are also a number of shallow depressions which may be collapsed burrows. The largest sand spread, in the floor of the shallow hollow traversed, was about 100 m across.

Lying on all surfaces, including the shell sand and rock exposures, is a dusting of mud, readily stirred up by the submersible and presumably rising into suspension in rough weather conditions.

### Glaciated Torridonian Sandstone Between Coll and Muck (70/10B)

The second traverse was made eastwards for 750 m across part of a shallower rocky bank. The dive was planned to investigate a series of small asymmetrical ridges shown on the echo sounder trace but too small to be clearly apparent on section C-D of Fig. 16.

Observation from the submersible established that the ridges in the first 1000 m of the traverse are small NE- facing rock escarpments striking at N 150°. Their dip slopes, which vary in gradient from 15° to 50°, appear to be controlled by poorly defined bedding planes dipping 15° to 20° to the south-west. The dip slopes normally comprise a series of small steps, and are steeper than the bedding; they level off before passing into steep scarp faces up to 10 m high. The surface of the rock is rounded, but uneven and pitted with small cracks and crevices. Many of the small fractures conform to a dominant N 150° trend.

At 1000 m from the dive location the submersible crossed a prominent ridge (Fig. 16, section C-D, a) and travelled a short distance to the east. The strike of its dip slope was N 150° but the orientation of the scarp face where the submersible crossed it was north-south. Eastwards from this vicinity occurs a steep sided east-west gully beyond which the constant N 150° strike is replaced by a more variable strike of about N 45°. East-west glacial striae were observed on a rock platform to the north of this gully.

An attempt to core the rock was unsuccessful as a current lifted and moved the submersible during drilling, damaging the core barrel, which would not then re-enter the hole drilled. The similarity of the terrain to that observed and cored on the first dive, together with the geophysical evidence, suggests that this bank is probably formed of Torridonian sandstones.

Apart from angular cobbles and boulders lying scattered on the rock surface and in small hollows and crevasses, sediment is concentrated in the depressions below the scarps and in the east-west gully. These are mostly floored with cobbles and boulders, but in one there is a coarse sand, with granule-grade shell debris, formed into ripples with rounded, symmetrical crests; their wavelength is 1·5 m and amplitude about 300 mm. In the centre of the hollow the ripples trend N 150° but towards the edge they curve round to meet the bounding cliff at an angle.

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APPENDIX 1: DETAILS OF PISCES DIVES WITH IGS STAFF IN 1969 AND 1970

| IGS Dive No | Date | Decca or Radar position at start* | Red | Green | Purple | Observers | Time on sea bed | Sea conditions |
|---|---|---|---|---|---|---|---|---|
| 69/1 | 8.11.69 | 2.2 miles from Mealdarroch Point: 1.8 miles from Rudha Mor | | | | R. A. Eden., S. Crampin | 2 50 | Short swell 2.5 m |
| 69/2 | 9.11.69 | 0.6 miles from Mealdarroch Point: 2.5 miles from En Aoidhe | | | | D. A. Ardus | 3 36 | Calm |
| 69/3 | 10.11.69 | 2.45 miles from Mealdarroch Point: 1.0 miles from En Aoidhe | | | | R. A. E., D. A. A. | 2 18 | Chop 1 m |
| 69/4 | 12.11.69 | 2.40 miles from Mealdarroch Point: 1.95 miles from Rudha Mor | | | | R. A. E., D. A. A. | 3 22 | Calm |
| 70/1A | 8.06.70 | 1.75 miles at N 115° from Rudh Aoineadh Mheinis | | | | R. A. E., G. Y. Craig | 1 47 | Calm |
| 70/1B | 8.06.70 | 1.40 miles at N 359° from N point Insh Island | | | | D. A. A., G. Holland. | 1 52 | Calm |
| 70/2A | 9.06.70 | 3B | J05.61 | A38.11 | J62.12 | P. E. Binns., J. B. Wilson | 3 52 | Long swell 2 m |
| 70/2B | 9.06.70 | 3B | J05.12 | A37.98 | J62.49 | R. A. E., R. McQuillin | 2 15 | Long swell 1 m |
| 70/3A | 10.06.70 | 6C | F22.60 | ------ | J59.95 | R. A. E., J. B. W. | 4 19 | Calm |
| 70/3B | 10.06.70 | 2.60 miles at N 89° from SE point Sandray | | | | D. A. A., G. H. | 4 11 | Calm |
| 70/4A | 11.06.70 | 3B | I20.29 | A36.60 | J53.71 | P. E. B., C. E. Deegan | 3 53 | Long swell 2 m |
| 70/4B | 11.06.70 | 3B | I18.00 | A36.02 | J56.82 | D. A. A., R. Floyd | 4 33 | Swell 0.5 m |
| 70/5A | 12.06.70 | 3B | I03.80 | A34.30 | J51.50 | R. A. E., J. Butler | 3 41 | Chop 1 m |
| 70/5B | 12.06.70 | 3B | I00.47 | A33.65 | J57.75 | D. A. A., P. E. B. | 3 28 | Calm |
| 70/6A | 13.06.70 | 6C | F13.70 | ------ | J57.10 | R. A. E., H. Robertson | 3 02 | Calm |
| 70/6B | 13.06.70 | 6C | F04.42 | ------ | J66.85 | P. E. B., C. E. D. | 4 11 | Calm |
| 70/7A | 14.06.70 | 6C | E12.70 | ------ | J76.90 | D. A. A., C. E. D. | 3 01 | Calm |
| 70/7B | 14.06.70 | 6C | E00.42 | ------ | A58.24 | P. E. B., R. F. | 2 35 | Calm |
| 70/8A | 15.06.70 | 2.00 miles from Rubha na' Leac: 2.70 miles from Sgeir Dhearg | | | | R. A. E., K. C. Dunham | 3 16 | Short swell 1.5 m |
| 70/8B | 15.06.70 | 2.00 miles at N 90° from Garbh Eilean | | | | D. A. A., A. McLean | 2 20 | Short swell 2 m |
| 70/9A | 16.06.70 | 3B | G15.50 | ------ | B70.76 | P. E. B. | 3 52 | Chop 1 m |
| 70/9B | 16.06.70 | 3B | G11.00 | ------ | B79.12 | D. A. A., N. G. T. Fannin | 4 05 | Chop 0.3 m |
| 70/10A | 17.06.70 | 3B | G07.89 | ------ | B77.90 | R. A. E., N. G. T. F. | 2 04 | Calm |
| 70/10B | 17.06.70 | 3B | G06.73 | ------ | B78.13 | D. A. A., P. E. B. | 2 52 | Calm |

* Decca positions are uncorrected and given in the order: Chain, red, green, purple
Radar positions are in nautical miles and bearing related to true north

## APPENDIX 2: PRELIMINARY OBSERVATIONS ON AN OCCURRENCE OF LOPHELIA IN THE SEA OF THE HEBRIDES

J. B. Wilson

National Institute of Oceanography

Following the discovery of considerable quantities of the dead coral Lophelia prolifera M. Edw. -H. in a dredge haul taken 13·5 km east of Mingulay by the R. R. S. John Murray in September 1968 a place was kindly provided by the Institute of Geological Sciences in the submersible Vickers Pisces to dive in the area of the dredge haul to investigate the nature and extent of the coral bank.

The coral bank itself was seen to occur towards and at the summit of a ridge striking N 120° at a depth of 105 m. At the top of the ridge the density of polyps was such that groups of corals displayed a close packed dendritic habit suggesting considerable competition for space and nutrients. At the summit 30 to 40 per cent of the polyps appeared to be living. Isolated colonies consisting wholly of living corals up to 10 cm across were observed. Lower down the ridge, however, almost all the polyps were dead and were colonised by ophiuroids, polychaetes, asteroids and crustaceans living in the shelter provided by the coral colony. The exposed surfaces of the corals were colonised by hydroids, anthozoans, tunicates and sponges.

The slope away from the ridge was of the order of 30° and the boulders and cobbles covering this slope supported a fauna including anthozoans, hydroids and the crinoid Antedon bifida (Pennant). The density of crinoids at this point was of the order of 10 per square metre. Away from the slope up to the ridge, at depths between 112 and 120 m, the crinoids became much more abundant and densities of the order of 80 to 100 per square metre were commonly noted. The crinoids were fairly uniformly spaced over the bottom, the spacing being apparently determined by the reach of each individual's arms, as little or no intermingling of the ends of the arms of adjacent individuals was observed. The fauna associated with the corals is sparse and consists of occasional alcyonarian colonies or isolated individual anthozoans.

## APPENDIX 3: OUTLINE SPECIFICATIONS OF VESSELS

Submersible Vickers Pisces

| | | |
|---|---|---|
| Dimensions: | Length | 19 ft 4 in |
| | Breadth | 9 ft 10 in |
| | Height | 10 ft 4 in |
| Displacement: | 26 500 lb | |

Internal diameter of main sphere: 6 ft 6 in

Power source: 55 kWh lead-acid oil-filled battery

Propulsion motors: 2 x 3HP

Maximum diving depth: 3500 ft

Atmosphere endurance: 60 hours for crew of 2

Buoyancy and trim: Vernier-controlled oil-transfer system

Lights: Two 1000-watt quartz-iodine lamps

Items which can be jettisoned: 400-lb detachable weight, batteries, propulsion motors, tooling

Certification: American Bureau of Shipping

R.V. Vickers Venturer

| | | |
|---|---|---|
| Dimensions: | Length | B.P. 117 ft 8 in, overall 122 ft 0 in |
| | Breadth | 25 ft 1 in |

Draught: Mean loaded 12 ft 4 in

Displacement: 630 tons

Freeboard: Stern 3 ft 0 in approx. Midships 8 ft 0 in

Propulsion: 2 x 394 HP diesel via single-screw variable-pitch propellor

Endurance: 21 days

Dd. 500635 K 8

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# Geological Structure in the Sea of the Hebrides

R. McQUILLIN & P. E. BINNS

Institute of Geological Sciences, London SW7

**Recent surveys show that the structural history of the Sea of the Hebrides is consistent with ideas about continental drift in the North Atlantic.**

GEOLOGICAL and geophysical investigations in the Sea of the Hebrides by the Institute of Geological Sciences have included an aeromagnetic survey[1], gravity and magnetic surveys from ships, shallow and deep reflexion seismic surveys, rock sampling using a variety of techniques and drilling from an anchored ship capable of up to 70 m penetration beneath the seafloor. A geological map and structural interpretation (Figs. 1 and 3) are based on these surveys together with recent detailed bathymetric data supplied by the Hydrographic Department of the Navy.

The evidence shows that the geology of the area is controlled by three principal faults—the Minch Fault, the Camasunary–Skerryvore Fault and the Great Glen Fault. A fault with a similar trend has been detected to the west of the Outer Hebrides. These faults form margins to deep asymmetric troughs which are floored by down-thrown Precambrian and Palaeozoic rocks and which are filled by Mesozoic rocks, of which New Red Sandstone, Jurassic and Cretaceous samples have been obtained. The chief features of the Bouguer gravity anomaly map (Fig. 2) can be interpreted directly in terms of

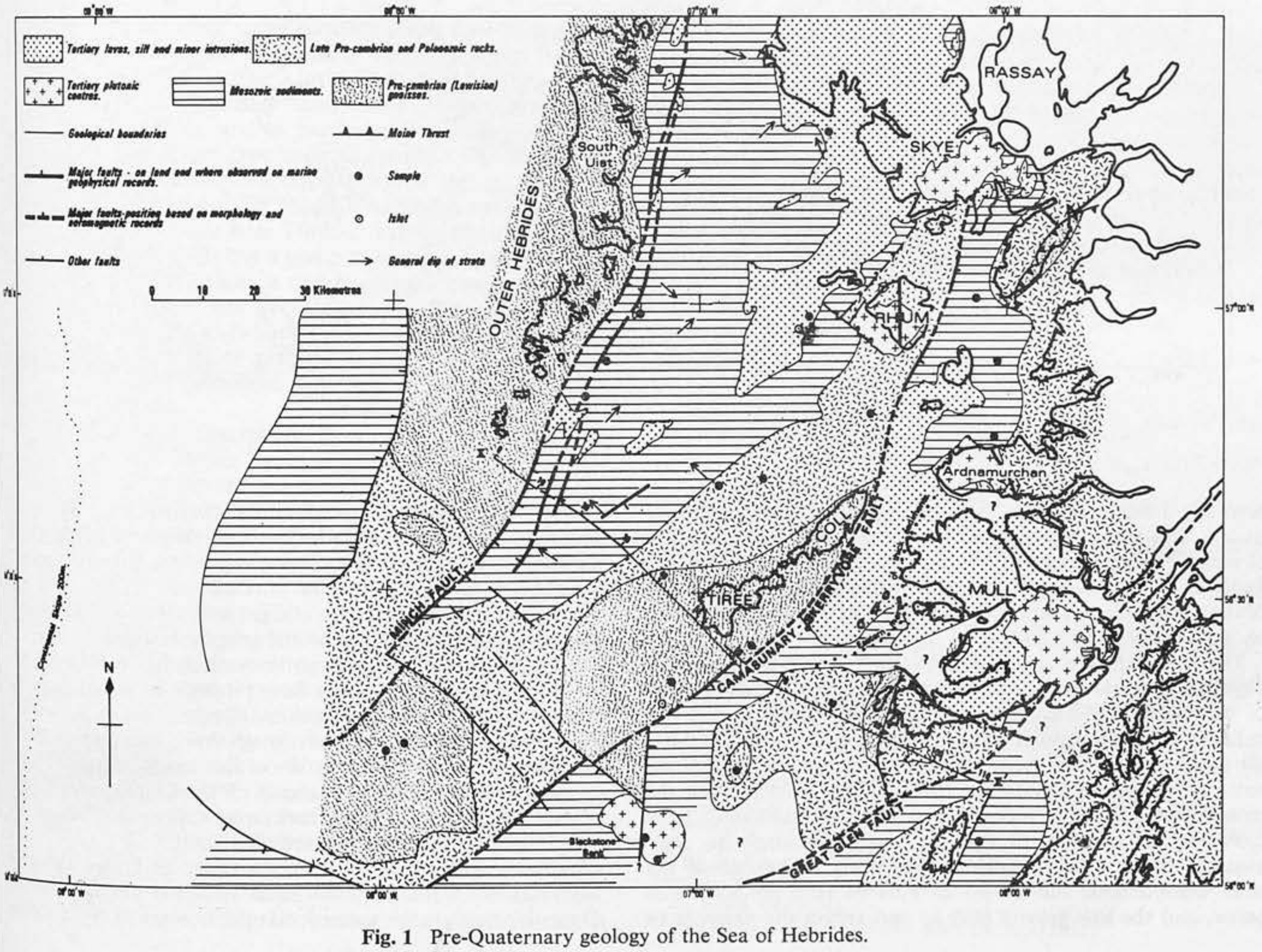


**Fig. 1** Pre-Quaternary geology of the Sea of Hebrides.

the deeper effects of geological structures mapped near the sea bed by predominantly seismic methods. No Tertiary sediments have been found but extensive areas of the sea are floored by Tertiary igneous rocks. Much of the area is covered by a variable thickness of glacial and post-glacial deposits.

The most extensive trough extends south-westwards from beneath the Skye Tertiary lavas until it wedges out against the Minch Fault approximately 30 km to the south of the Outer Hebrides: this we call the Sea of the Hebrides Trough. A second trough, with parallel trend, lies to the east; it is controlled by the Camasunary–Skerryvore Fault, and is called here the Inner Hebrides Trough. Less well defined is the trough that lies to the west of the Outer Hebrides, only part of which has been investigated: this we call the Outer Hebrides Trough. A fourth area of Mesozoic rocks lies to the south-east of the Great Glen Fault, but little information is yet available on the south-westerly extent of this trough.

The Sea of the Hebrides Trough is probably thickest beneath Skye[2], where interpretation indicates the presence of 2.5 km of New Red Sandstone and younger rocks. Seismic evidence indicates that the trough has an uneven floor with a general tilt down to the north-east. In the south-west this causes the basin to wedge out against the Minch Fault. Throughout the trough, the Mesozoic succession is probably underlain by a considerable thickness of Palaeozoic and Precambrian sedimentary rocks. The Torridonian is likely to be one of the chief components, but in places Palaeozoic rocks may also occur, and the low gravity may in part reflect the presence of Old Red Sandstone or Carboniferous sediments. Mesozoic rocks are identified on the seismic records by their regular bedding and relatively low velocity. Rock samples taken from the seafloor above the deeper parts of the basin have yielded microfossils of Jurassic or Cretaceous age. A seafloor sample from the margin has been identified as Permo–Triassic, and other outcrops of Permo–Triassic occur on Rhum and Skye[3,4]. Thicknesses of the Jurassic as seen in troughs on land suggest that rocks of this age are not likely to form the principal component of basin infill, and the presence of a thick Permo–Triassic sequence is therefore suggested.

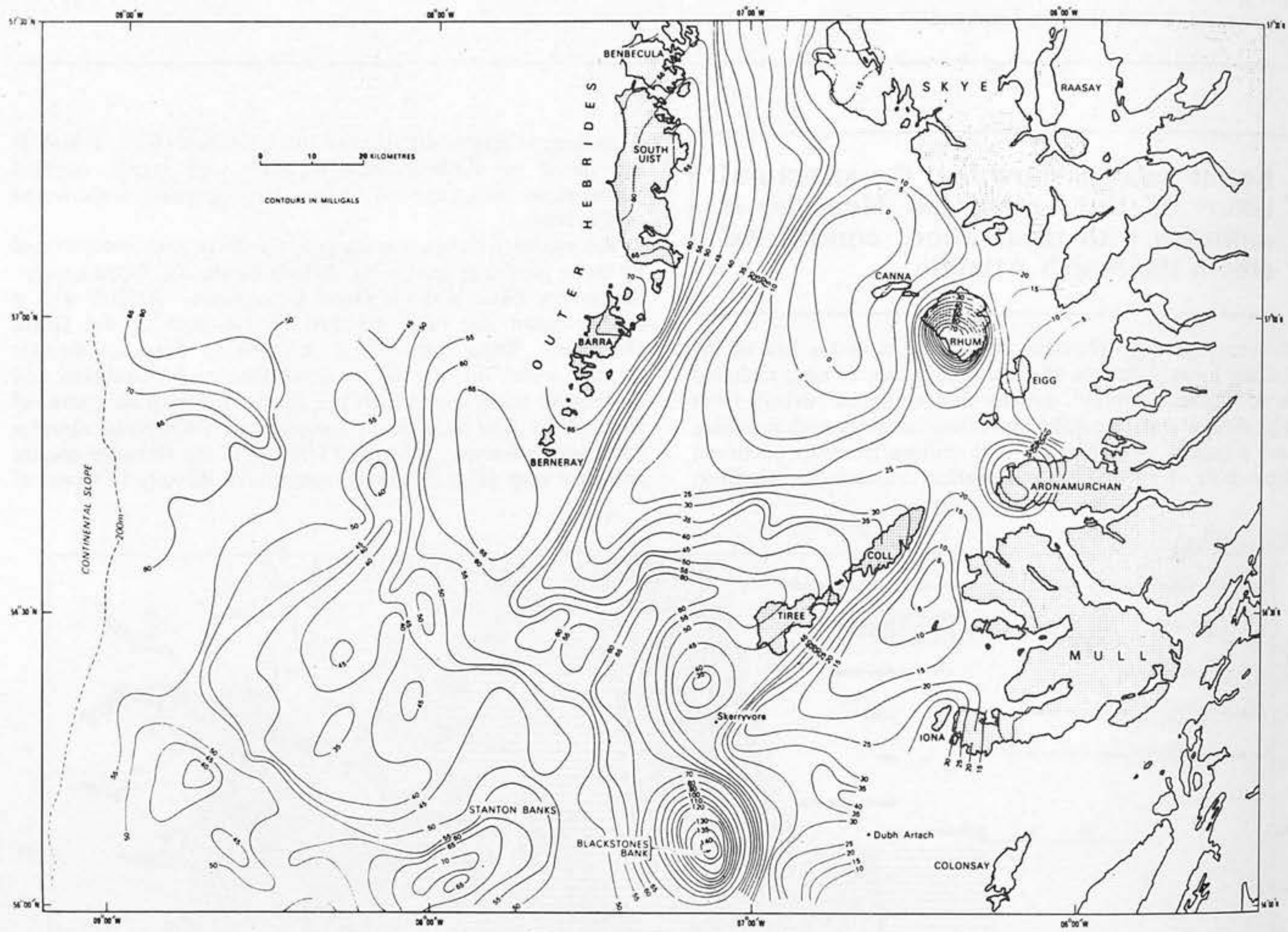


**Fig. 2** Bouguer gravity anomaly map, contours at 5 mgal intervals.

The Inner Hebrides Trough is narrower than the Sea of the Hebrides Trough, but the maximum thickness of infilling sediments is of the same order according to the gravity anomaly which lies to the south-east of Coll and Tiree. For this anomaly a model with 3 km of light sediments wedged against the fault gives the best fit to the geophysical data. Much of the deeper part of this trough is overlain by Mull lavas, and no sedimentary rock samples have yet been obtained from the seafloor south of Ardnamurchan. Samples from the seafloor in the northern part of the trough have been identified as Jurassic. The asymmetric nature of this trough is again evident in South Skye, 13 km to the east of the Camasunary Fault[5], where Triassic and Liassic rocks rest unconformably on the Torridonian, thickening towards the fault.

Gravity evidence shows that the Outer Hebrides Trough is asymmetric in the opposite sense to those discussed above. Over this trough the eastern margin is marked by a steeper gradient and larger change of gravity level than that observed over the western margin. Little seismic evidence is available at present and no rock samples have so far been obtained.

The trough that lies to the south-east of the Great Glen Fault has been identified on deep and shallow seismic records and has an associated gravity anomaly. The area so far investigated, however, only includes the north-eastern extremity of what may be a large trough extending along the Great Glen Fault to the south-west.

Gravity, magnetic and seismic records combine with sampling and bathymetric evidence to confirm the existence of a Minch Fault system, indicate a large south-westerly extension of the Camasunary Fault, here referred to as the Camasunary–Skerryvore Fault, and, furthermore, provide new evidence on the line of a submarine extension of the Great Glen Fault.

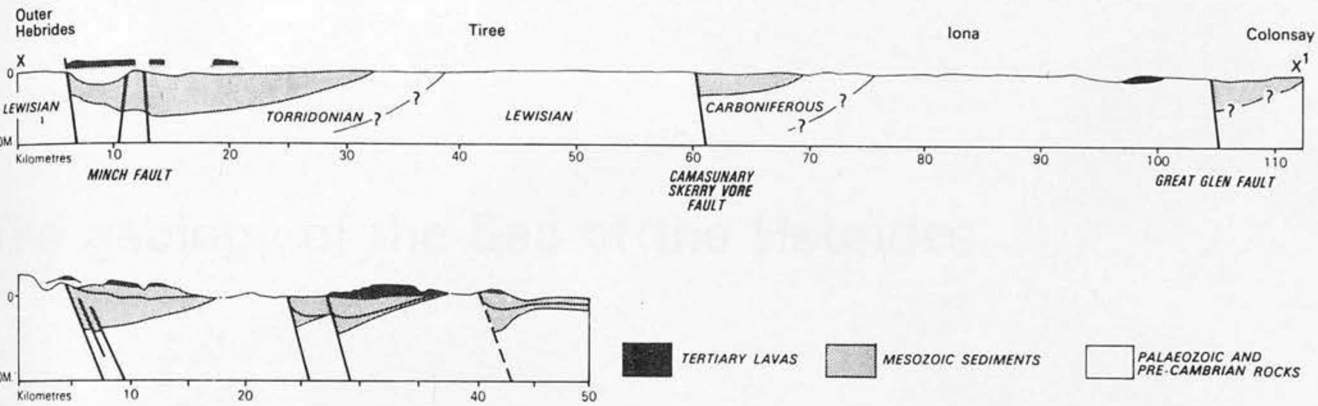


**Fig. 3** Section of structure in the Sea of Hebrides compared with section (after Vischer[14]) in East Greenland.

The course shown in Fig. 1 for the Minch Fault differs from that proposed by Dearnley[6] and earlier workers on chiefly bathymetric grounds, and in particular it is seen to be more curved than has been previously suggested. Off South Uist the fault trace curves northwards to follow the trend of the Outer Hebridean coast and through its length follows closely the trend of the Outer Isles Thrust. Furthermore, it appears to be not a single fault but a complex system of normal faults. Our work gives no evidence of transcurrent movement. The Minch Fault system has probably had a long and complex history, initiated as a Caledonian structure, possibly reactivated by Hercynian stresses to give transcurrent displacement and finally reacting to Mesozoic and Tertiary tension with large vertical movement.

The Camasunary–Skerryvore Fault is similar in trend and magnitude to the Minch Fault, although its history is known only from its exposure on Southern Skye and Raasay. Geological evidence suggests a Jurassic movement followed by a lesser movement in the Tertiary[7].

The south-westerly continuation of the Great Glen Fault suggested in Fig. 1 does not follow a linear extension of its course through the Great Glen. We consider it possible that the boundary mapped geophysically by us, which is seen on reflexion seismic records as a line of large vertical displacement in Mesozoic rocks, may have developed along a more easterly trending branch of an earlier complex of faults.

One of the chief features of the map is the off-shore extent of Tertiary igneous rocks. It does not include the many Tertiary dykes discovered by geophysical methods, but shows the large lava covered areas and indicates the significance of the Blackstones Tertiary Centre which is probably a similar structure to that in Rhum[8]. Specimens of ultrabasic rock have been collected from the Blackstones Bank by the Institute[9]. The gravity anomaly (Fig. 2) observed over this structure is larger than that observed over any other Hebridean Tertiary Centre. Apart from Tertiary movement on the principal fault lines, the geological map indicates the significance of Tertiary cross-faulting on the trough margins.

The Mesozoic basins in and around the Sea of the Hebrides have developed by down-faulting in an area of extensive Mesozoic sedimentation which probably included the shelf west of Shetland and, before continental drift, the shelf and eastern land area of Greenland[10,11]. Structure similar to the Sea of the Hebrides has been described for the area west of Shetland[12] and for the Rockall plateau and trough[13]. The similarity of structure between the Sea of the Hebrides and Greenland is illustrated by comparing the sections in Fig. 3.

The structural history of the Sea of the Hebrides is therefore consistent with current proposals concerning continental drift in the North Atlantic[11,15]. Sedimentary basins developed in the zone that was later to fracture, leading to the separation of Greenland from north-western Europe and the Rockall Plateau in early Tertiary times. Block faulting occurred before this split, possibly related to the opening of the Rockall Trough in the Mesozoic[15,16]. Tertiary igneous activity was accompanied by north-west–south-east cross faulting and further block faulting occurred after igneous activity had ceased.

This analysis has been undertaken as part of the research programme of the Institute of Geological Sciences.

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INSTITUTE OF GEOLOGICAL SCIENCES

Report No. 73/14

# The geology of the Sea of the Hebrides

P.E. Binns, BSc, R. McQuillin, MSc and N. Kenolty

with contributions by R. W. Elliot, BSc, G. Warrington, PhD, H. C. Ivimey-Cook, PhD,

R. Harland, PhD, M.J. Hughes, BSc and B. Cooper, PhD

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and the Museum of Practical Geology with
Overseas Geological Surveys and is a constituent body
of the Natural Environment Research Council



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## PREFACE

This report brings together the results of a number of geological and geophysical surveys in the Sea of the Hebrides undertaken by the Institute of Geological Sciences between 1968 and 1971; the work forms part of the Institute's reconnaissance survey of the British continental shelf.

A map of pre-Quaternary geology is presented and discussed in detail. The account also includes a brief description of the Quaternary geology based on field evidence and such laboratory results as are available, but a more detailed account of this aspect of the geology of the area is in preparation.

The following staff of the Institute directed parts of the work at sea: Messrs R.A. Eden, D.A. Ardus and P.E. Binns of Continental Shelf Unit II; Messrs R. McQuillin, M. Tully, N. Kenolty and Dr J. Sunderland of the Marine Geophysics Unit. Mr J. Butler supervised sampling operations on the Vickers Venturer (September 1970) and Surveyor (August-September 1971) cruises. Messrs R.A. Eden and R. McQuillin were responsible for overall organisation of the work.

The Hydrographer to the Navy is thanked for his permission to incorporate recent unpublished data from Hydrographic Department surveys in Fig. 3. The interpretation of this data is, however, solely the responsibility of the authors.

Dr J. Tuson of the University of Durham is thanked for his permission to use gravity data relating to the Isle of Skye.

Kingsley Dunham
Director

Institute of Geological Sciences
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South Kensington
London SW7 2DE
1 September 1973

CONTENTS

ILLUSTRATIONS



* Note: In Fig. 2 the fault-bounded triangle north of Blackstones Plutonic Centre is Lewisian gneiss, not Mesozoic sediment as shown.

## Summary

A map of the pre-Quaternary geology of the Sea of the Hebrides, based on geophysical and sampling evidence, is presented. The Minch, Camasunary-Skerryvore and Great Glen faults, which are major controlling factors in the geology of the inner shelf, have been mapped across the area. The Minch and Camasunary-Skerryvore faults form the western margin of two asymmetric troughs floored by Precambrian and Lower Palaeozoic rocks and filled with Upper Palaeozoic and Mesozoic sediments. Such evidence as is available suggests that these troughs have a complex history, originating as Caledonian structures and being reactivated during the Mesozoic and Tertiary. A third asymmetric trough has been detected on the outer shelf. Although the Great Glen Fault is shown to affect sedimentary rocks offshore the age of the rocks associated with it is not yet known.

Tertiary igneous activity and cross-faulting exert important secondary control on the geology. The submarine extensions of the Mull and Skye lava flows have been mapped, as has been the Blackstones plutonic centre. Cross faulting, together with tilting of the faulted Sea of the Hebrides Trough, has brought seismic basement to the surface in the south of the area.

A preliminary account of the Quaternary geology is given. A glaciated rock surface, trenched by overdeepened hollows is overlain by variable thicknesses of boulder clay and late glacial and postglacial marine muds. Microfauna in the latter possibly indicate a sequence of climatic changes.

A thin cover of modern sediment lies on the older deposits: the distribution of facies is controlled primarily by water depth, degree of exposure to the prevailing south-westerly swell and the presence or absence of sea floor outcrops.

## Sommaire

Sur la base d'échantillage et d'évidence géophysique, on présente une carte de la Mer des Hebrides. Elle montre le Minch et les failles de Camasunary-Skerryvore et du Great Glen, qui sont des facteurs d'importance majeure qui gouvernent, en grande partie, la geologie de la plate-forme intérieure.

Le Minch et les failles de Camasunary-Skerryvore forment la marge à l'ouest de deux fosses d'effondrement asymétriques au fond desquels se trouvent des roches du précambrien et du paléozoïque inférieur, et qui sont remplis de sédiments paléozoïques et mésozoïques. L'évidence disponible suggére que l'histoire de ces fossés est très complexe puisqu' ils avaient leur origine pendant le calédonien et qu' ils étaient réactivés pendant le mésozoïque et le tertiaire. On a découvert une troisième fossé asymétrique sur la plate-forme extérieure. On a démontré que le Great Glen Fault exerce une influence sur les roches sedimentaires au large, mais l'âge des roches, qui y sont associées, n'est pas encore connu.

L'activité ignée tertiaire et des failles perpendiculaires exercent une influence secondaire sur la géologie. On a dressé la carte des extensions sousmarines des coulées de lave de Mull et de Skye et aussi du centre plutonien de Blackstones. Les failles perpendiculaires avec le basculement du fossé faillé de la Mer des Hebrides ont élevé le soubassement sismique au surface au sud de la région.

On fait un exposé preliminaire de la géologie quaternaire. Une surface de roches, érodée par des glaciers et creusée par des bas-fonds enfoncés est recouverte par des argiles à blocaux d'épaisseur variée et par des boues marines glaciaires récentes ou post-glaciaires. Il se peut que la microfaune dans ces boues post-glaciaires indique une succession de changements de climat.

Une couverture mince de sédiments modernes se trouve sur les dépôts plus anciens; la distribution de faciès est réglée surtout par la profondeur de l'eau, par le degré d'exposition à la houle régnante du sud-ouest, et par la présence ou l'absence d'affleurements au fond de la mer.

## Zusammenfassung

Hiermit bietet man eine Karte der Präquartärgeologie vom Hebridenmeer, die auf geophysischem Musternachweis gegründet ist. Die Minch, Skerryvore und Great Glen Verschiebungen, die wichtige entscheidende Umstände in der Geologie des inneren Schelfes sind, sind über das Gebiet

Kartographisch gestellt. Die Minch und Camasunary-Skerryvore Verschiebungen bilden den westlichen Rand von zwei asymmetrischen Mulden, wovon Präcambrium-hund Unterpaläozoisch gesteine den Boden bilden und die von Oberpaläozoischen- und Mesozoischen-Sedimenten gefüllt sind. Der verfügbare Nachweis lässt denken, dass diese Mulden eine komplizierte geschichte haben, die als Kambriumstrukturen enstanden und wahrend des Mesozoikums und des Tertiärs reaktiviert waren. Man hat eine dritte asymmetrische Mulde auf dem ausseren Schelf entdeckt. Obgleich man den Nachweis erbracht hat, dass die Great Glen Verschiebung die Sedimentgesteine in Küstennähe beeinflüsst hat, ist das Alter der damit verbundenen Gesteine noch nicht bekannt.

Tertiärvulkanische Aktivität und Kreuzverschiebung haben einen wichtigen Sekundäreinfluss auf der Geologie. Man hat von den Unterwasserausdehnungen Karten gemacht, wie auch vom Blackstones plutonischen Zentrum. Kreuzverschiebung zusammen mit Kippung vom verschobenen Meer der Hebrides-Mulde hat im Süden des Gebiets den seismischen Basis zur Oberfläche gebracht.

Eine einleitende Erklärung der Quartärgeologie wird gegeben. Veranderliche Schichte von Blocklehn und späteiszeitige und nacheiszeitige Meereschlämme bedecken vereiste Gesteinoberfläche, die von übervertieften Höhlen geschnitten ist. In der Meereschlämmen ist es möglich, dass Mikrofauna eine Folge von klimatischen Veränderungen zeigen.

Eine dünne Decke des modernen Sediment liegt auf der älteren Ablagerung. Die Faziesverbreitung wirk hauptsächlich von Wasser tiefe, Grad der Aussetzung zum herrschenden südwestlichen Dünung und der An- oder Abwesenheit der Seebodenausbisse beherrscht.

# The geology of the Sea of the Hebrides

P. E. BINNS,[1] BSc, R. MCQUILLIN,[2] MSc and N. KENOLTY[2]

## Introduction

This report summarises the results of a number of investigations carried out by the Institute of Geological Sciences in and around the Sea of the Hebrides. The work constitutes part of the Institute's reconnaissance survey of the British continental shelf, and as such provides a geological framework within which detailed research can be pursued.

The area covered is shown in Fig. 1. Work commenced in 1968, the area being the first in Scottish waters selected for regional study by the Institute. Over the years 1968-71 a substantial body of new geophysical and geological data has been collected. Aeromagnetic and land geophysical surveys, mainly undertaken before 1968, are discussed here where they have relevance to our interpretation of the offshore geology. Individual projects are listed in Table 1 and described in Appendix 6.

The main objective has been to prepare a map, in as much detail as possible, of pre-Quaternary geology. A preliminary account only is given here of Quaternary geology, a detailed study of which is in progress in conjunction with the University of Edinburgh. Studies are also in progress on the deep structure of the area through analysis and interpretation of deep seismic and gravity data in conjunction with the geology departments of the Universities of Glasgow and Durham.

## Geological Context and Previous Work

The geology of the western highlands and islands of Scotland is complex; the area was deeply eroded during late Tertiary and Pleistocene times and a great variety of rock types is now exposed. This section briefly describes the geology of the adjoining mainland and islands and reviews work referring to the marine area (Fig. 2).

### *PRECAMBRIAN TO MIDDLE TERTIARY*

A Caledonian thrust belt separates a foreland group, consisting of late Precambrian (Torridonian) and Cambro-Ordovician unmetamorphosed sediments resting on Precambrian Lewisian gneisses to the west, from a metamorphosed group of mainly psammitic schists (Moine) to the east (Phemister, 1960, p. 55). North of Skye the thrust belt crops out on the mainland and trends south-south-west to cross the coast onto Skye. South of Skye the thrusts themselves are not seen, but the position of the uppermost (Moine) thrust has been traced between the respective positions of foreland and schist groups.

West of this thrust belt the foreland group forms a basement upon which later formations have been deposited. Both Lewisian and Torridonian rocks outcrop on most of the islands of the Hebrides, and Lewisian rocks form the islands of Coll, Tiree and those islands of the Outer Hebrides covered by this report. To the east of the Moine Thrust the Moine Schists form a metamorphic basement, together with a second group of Caledonian metasediments, the Dalradian.

Devonian conglomerates, sandstones, shales and lavas rest unconformably on Dalradian schists on Lorne and at least 12 m of Carboniferous sandstones with shale beds and one coal seam occur on Morven (Johnstone, 1966, p. 69; Lee and Bailey, 1925, p. 22, 56).

Hercynian stresses produced major north-east-trending wrench faults including the Great Glen and Strathconan faults (Kennedy, 1946). Kennedy estimates sinistral movement on the Great Glen fault to be of the order of 100 km.

In the Inner Hebrides Mesozoic sediments, lying unconformably on earlier formations, have been protected from erosion by overlying Tertiary lavas (Richey and others, 1961, p. 20), the main outcrops being on Skye, Raasay and Mull with smaller ones on the other islands of the Inner Hebrides and on the mainland. The succession varies with locality but an overall pattern can be recognised. Red beds of Permo-Triassic age are preserved in down-faulted basins and hollows in older rocks and in places these pass conformably upwards into Jurassic

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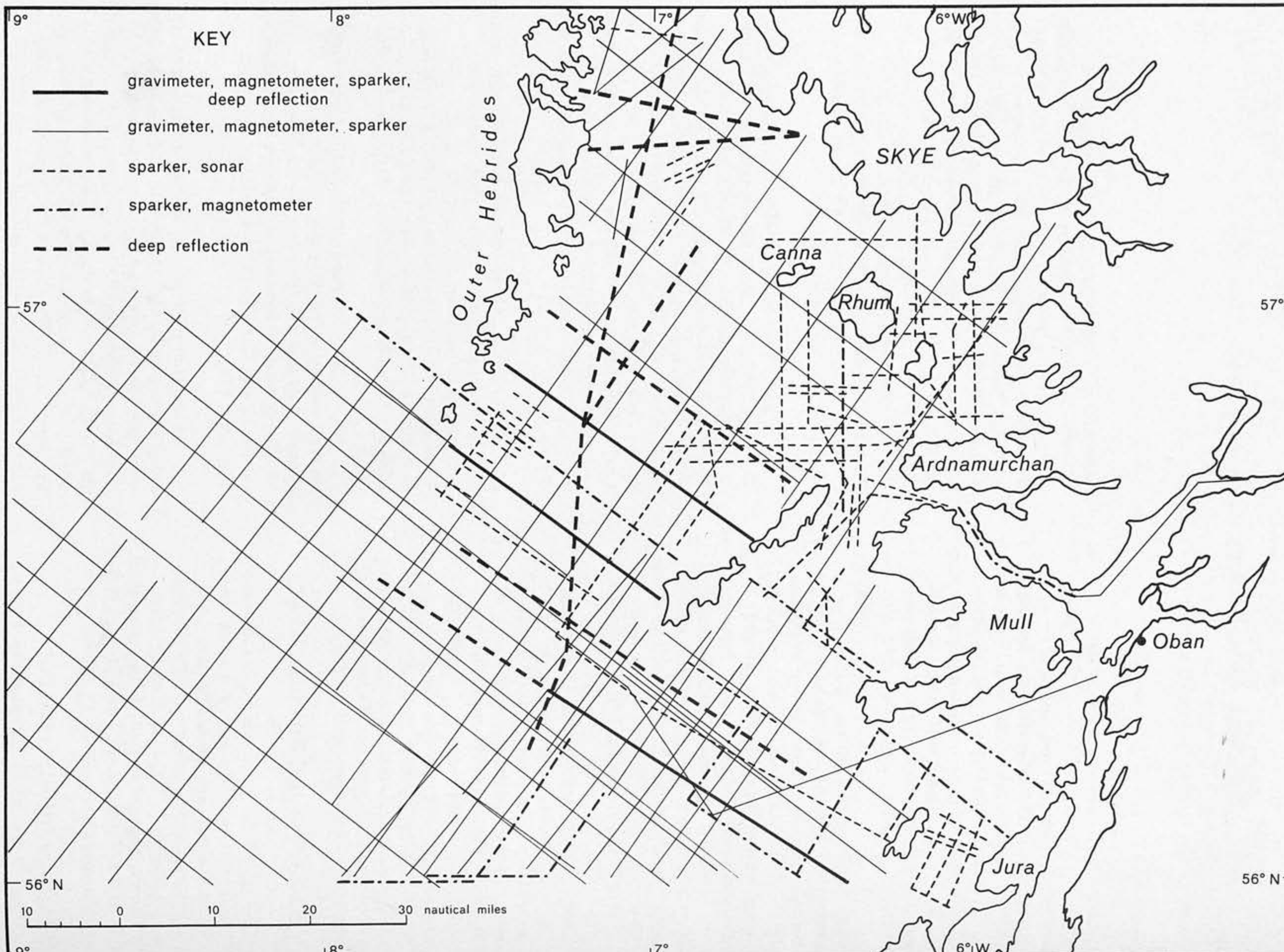


Fig. 1. Geophysical surveys

marine sediments some 900 m thick. Upper Cretaceous marine sediments up to 20 m thick rest unconformably on an eroded Jurassic surface and overstep older formations, thus indicating a phase of mid-Mesozoic movements. Further movement occurred during early Tertiary times and one of the main results of the present work is the evidence it provides for a major tectonic event at this time involving the rocks of the region in large scale block faulting. To the south-east of the Camasunary Fault on southern Skye Mesozoic sediments were downthrown at least 650 m against Torridonian sandstones (Peach and others, 1910, p. 150). This is a major structure which can be traced both northwards across the island of Raasay and southwards where it is believed to run east of the islands of Rhum (Torridonian) and Coll (Lewisian) but west of the Mesozoic outcrops on Eigg Island and the Ardnamurchan peninsula. Below we present evidence for the continuation of this fault further southwards past the Skerryvore Bank and the Stanton Banks and in this region we have referred to it as the 'Camasunary-Skerryvore' fault (Fig. 2).

In places a thin basal Tertiary sequence of conglomerates, sandstones and lignites of Eocene age rests on older rocks and passes upwards into a persistent mudstone. The sequence is best seen in Mull where it is up to 6 m thick (Bailey and others, 1924, p. 53).

Here the sedimentary sequence ends and the base of a thick pile of Eocene basaltic lavas marks the start of a major episode of volcanic activity (Richey and others, 1961, p. 41), though on northern Skye tuffs intervene between sediments and lavas (Anderson and Dunham, 1966, p. 73). Intrusive complexes on Skye, Mull, Rhum and the Ardnamurchan peninsula represent a younger expression of the igneous activity, and are broadly contemporaneous with the emplacement of north-west trending dyke swarms. These dyke swarms are associated in places with north-west trending faults which on Skye have maximum throws of about 400 m. Post-lava movement on the Raasay Fault is suggested by the evidence of lavas on the south-east of the fault lying at a lower level than Torridonian rocks to the north-west.

Previous writers have looked to the bathymetry of the area for evidence of the large scale geological structure. In particular, attention has centred on the main channel of the Sea of the Hebrides and the scarp which forms its western margin. Mackinder (1907, p. 75) was first to propose that it represented a submerged rift valley and this suggestion was taken up by others (reviewed by George, 1966, p. 16). George pointed out the absence of any evidence of an eastern margin to the rift and favoured the explanation that the elongated troughs mark a fault line. The suggestion of a major fault in the Minch, made by Ting (1937, p. 79) and Holtedahl (1952, p. 219) was later taken up by Dearnley (1962) who explained the discordance of structural zones in the Lewisian of the mainland and Outer Hebrides by sinistral movement on a Minch Fault; this fault being analogous to the Great Glen Fault. All three writers also noted the trenches on the east side of Coll and Tiree and suggested that these may represent the continuation of the Strathconan Fault.

Dykes on Islay and Jura appear to be centred on a plutonic centre to the north-west of Islay (McCallien, 1932, p. 51). Such a centre has since been confirmed by geophysical evidence (Bullerwell, 1963, p. 67; 1972, p. 211; Roberts, 1970).

### *LATE TERTIARY TO THE PRESENT DAY*

During late Tertiary and Pleistocene times the area was extensively eroded and considerable thicknesses of rock were removed to uncover Tertiary plutonic complexes; in addition a pulsed emergence of the land is indicated by the remains of plateaux and benches at various levels (George, 1966; Sissons, 1967, p. 15).

No late Tertiary deposits exist and most Pleistocene interglacial deposits have been eroded during the last glaciation; those that remain are isolated and have not been correlated with the glacial-interglacial sequence present in England (West, 1968, p. 235). Locally, raised cliff lines eroded by ice are believed to mark interglacial shores.

Most erosional and depositional evidence remaining today relates to the last (Devensian) ice age. Erosional landforms are dominantly glacial; boulder clay covers much of the lower ground and outwash fans and other fluvioglacial deposits are common.

Striae and erratic boulders indicate the east to west movement of an ice sheet across the area. The ice originated in the Western Highlands and spread radially out across Scotland and the Hebridean islands. Locally the ice was deflected by high ground in Mull, Rhum and Skye, and ice from these centres formed valley glaciers as the main ice sheet decayed. Erratics found in the Outer Hebrides include ?Cretaceous chalk, Triassic sandstones and Carboniferous limestone (Jehu and Craig, 1923, p. 440; 1925, p. 639) suggesting that these formations may form part of the sea floor to the east.

Following the last glaciation the decay of the ice was interrupted by three 'late glacial' readvances (Sissons, 1967, p. 125). The land, relieved of the weight of the ice, rose and at the same time world wide de-glaciation resulted in a eustatic rise in sea level. Close to the centre of the ice sheet uplift was at a maximum and remnants of late glacial shorelines are found some 25-30 m above present sea level; in places these are associated with outwash fans. Younger shorelines, including a well defined postglacial one, (the '25-ft bench') occur at lower levels.

The amount of isostatic uplift decreased away from the Western Highlands resulting in an inclination of the older beaches. Although the evidence for this is clearest on the eastern side of the Grampians, evidence from Ireland and from the coast northwards from Mull indicates that the same process has occurred on the west coast (Synge and Stephens, 1966; Sissons, 1967, p. 170, 199). This is consistent with evidence of the recent submergence of the Outer Hebrides, where isostatic uplift has failed overall to exceed eustatic rise in sea level.

The history, however, is not simple. At the end of late glacial times isostatic uplift throughout the area exceeded the eustatic rise in world sea level and the sea fell to near present sea level, permitting the growth of peat. Later it rose again, inundating the peat and culminating in a prominent postglacial shoreline some 8 m above present sea level in Mull and Lorne. Isostatic readjustment continued, lowering the shoreline to its present level and recent evidence shows that parts of the Scottish mainland are still rising slowly (Sissons, 1967, p. 213).

## Bathymetry

The bathymetric map (Fig. 3) has been compiled from published and unpublished Admiralty charts and surveys. Recent detailed bathymetric surveys made by the Hydrographic Department of the Ministry of Defence (Navy) cover much of the area of the main channels of the Sea of the Hebrides, the Little Minch and the Firth of Lorne and part of the shelf and slope west of Stanton Banks. This new data has been incorporated in Fig. 3.

The map shows a glaciated inner shelf extending westwards to Stanton Banks and the islands of the Outer Hebrides, forming a marked contrast to a comparatively flat outer shelf. The top of the continental slope lies between 140 m and 180 m. Hydrographic Department surveys (K2706/1 and K5223) and an unpublished manuscript map (D. G. Roberts, personal communication) indicate that it has a uniform gradient of 1 in 10 (6°) down to 1200 m. Here the slope between 56° N and 57° N is broken by the Hebrides Terrace Seamount (Roberts, 1971) which diverts the contours some 70 km to the west.

On the outer shelf there are shallow depressions lower than the top of the continental slope. Stanton Banks together with the southern islands of the Outer Hebrides and the shoals south of these islands, form the eastern margin of the outer shelf. Although the coastline of the Outer Hebrides is embayed two well defined trends are present on the east coast. From Berneray to Eriskay the coast forms a straight line trending north-east and north of Eriskay it describes a regular curve which continues into the Minch. A longitudinal trench up to 275 m deep, consisting of a series of hollows, runs parallel to the coast east of the Outer Hebrides; south of Eriskay a single channel parallels the coastline, but is broken by steep sided shoals off Pabbay Island. It terminates as an overdeepened hollow south-east of Berneray Island. North of Eriskay this north-east trending channel is absent. A feature with this orientation is however formed by the ends of overdeepened hollows which originate amongst shoal areas extending for some 10 km off the coast. Between Benbecula and Skye a broad hollow again follows a north-easterly trend. An adjacent line of depressions runs south-westwards from Canna Island and converges on the main channel off Berneray.

The islands and shoals of the Inner Hebrides are dissected by overdeepened hollows and the coastlines are embayed with fjords. A strong north-east trend is dominant in the Firth of Lorne area and is also evident further north on the coast of Skye, in the Sound of Sleat, between the islands of Rhum and Eigg, off the east coast of Coll and off the west coast of Ardnamurchan. In contrast the troughs north of Hawes Bank, Loch Sunart and the Sound of Arisaig trend east-west, and the Sound of Mull from south-east to north-west.

In the south an even sea floor is broken by rock shoals, the largest of which form Stanton Banks and the Blackstones Bank.

The bathymetry is similar to that of other glaciated shelves although the relief is not so strong. In particular it compares with the Norwegian Shelf in the vicinity of the Lofoten Islands. Holtedahl (1952) has drawn attention to the analogous positions of the Lofoten-Versterälen Islands and the Outer Hebrides, and has compared the two outer shelves.

## Geophysical Results

### *AEROMAGNETIC ANOMALY MAP*

The aeromagnetic total-force map shown in

Fig. 4 has been prepared from previously published data: sheets 10 and 12 of the Aeromagnetic Map of Great Britain and Northern Ireland, National Grid Diagram Edition, scale 1:250 000, with necessary modification to accomodate reduction in scale. Contour values represent magnetic anomalies measured in gammas against the linear regional field equation for the British Isles which implies a regional increase in total force of 2.1728 gamma/km northwards and 0.259 gamma/km westwards (National Grid directions) and a datum value of 47033 gamma at the grid reference origin for the epoch 1955.5. The map is used here to interpret aspects of the structural geology and discussion is limited to major features.

Two dominant magnetic trends are evident. A north-west trend is associated mainly with Tertiary dyke swarms focusing on Mull, Skye and, to a lesser extent, on other centres. This trend is characterised by short wavelength anomalies generally associated with secondary structural effects. On a broader scale, a south-west trend is associated with the structural elements; Caledonoid structure in basement rocks, and younger Mesozoic to Tertiary faulting which exerts principal control over the distribution of younger sedimentary and volcanic rocks.

A belt of relatively low magnetic values extends from south-east of Barra, north-eastwards into the Little Minch. This belt is characterised by generally low gradients disturbed in places by short-wavelength anomalies probably associated with minor intrusive bodies. This main belt of magnetic low relates to the main Sea of the Hebrides area of non-magnetic sedimentary rocks. The relationship is not simple, however; limits of the belt do not in all places correspond to the limits of structures containing sedimentary rocks as the whole pattern is complicated by the effects of minor intrusions and Tertiary volcanics. For example, the Canna Ridge is marked by a pattern of large magnetic fluctuations; but this is almost certainly due to the presence of a covering layer of basalts overlying a thick Mesozoic sequence.

Thus, the magnetic data provides evidence for the presence of a moderate sized sedimentary basin and on geological grounds it is expected that this basin will include formations down to and including the Torridonian as well as the Mesozoic; but because of the effects of the older rocks, and minor intrusions, depth interpretations to magnetic basement are expected to give a most unreliable indication of Mesozoic thicknesses. Furthermore, the magnetic anomaly pattern is not likely to correlate well with the areal distribution of Mesozoic rocks.

Two major south-west trending belts of positive anomaly occur, within which there are many large amplitude variations. Both can be correlated in places with partly subaerial, partly submarine ridges of Lewisian rocks. One belt extends, mainly offshore, along the south-eastern coasts of the string of Outer Hebridean islands from Eriskay through Barra to Mingulay, continuing south-westwards beyond the limit of the area surveyed. A second belt extends from west of Muck, south-westwards through Coll and Tiree, continuing along this trend, again beyond the limit of the area surveyed. In both cases, the magnetic data provide important evidence of the limits of the Lewisian outcrop.

The south-eastern limit of the Outer Hebrides belt is a well-defined line which marks the position of the western branch of the Minch Fault. Similarly the south-eastern limit of the Coll-Tiree belt is interpreted as marking the line of a major fault (the Camasunary-Skerryvore Fault). A third, less well-defined, positive magnetic belt extends from near Staffa, south-westwards through Iona, to the + 500 gamma high north-west of Dubh Artach. A step in this feature is probably related to block faulting in sedimentary rocks, and it is known from the seismic evidence that most of the belt is underlain by sedimentary rocks, at or near the sea floor. It is suggested therefore that the Lewisian rocks of Iona are part of a larger basement ridge much of which is overlain by a variable but relatively thin cover of Torridonian and younger sedimentary rocks.

The Tertiary volcanic centres of Skye, Mull, Ardnamurchan and Rhum are all associated with characteristic large amplitude arcuate anomaly patterns. A similar pattern has been detected over the Blackstones Bank, which was recognised by Bullerwell (1963, p. 67) as a strong indication of a Tertiary igneous centre. Confirmation of this interpretation is discussed below.

Magnetic evidence for the south-westerly extension of the Great Glen Fault is the remaining major feature to be discussed. Surprisingly, this line is not well marked on the magnetic map. Through Mull, its course is obscured by the intricate anomaly pattern which is caused by rocks of the Tertiary igneous complex and associated dyke swarm. South-westwards from Loch Buie a poorly defined lineation is detected where the fault probably throws sedimentary rocks on the south-east flank against Moine rocks to the north-west. This linear feature is recognised again south-east of the Blackstones Bank anomaly, however between these areas the probable line of the fault is ill-defined, mainly because of interference from anomalies associated with a group of north-west trending intrusions which extend from Islay to Skerryvore.

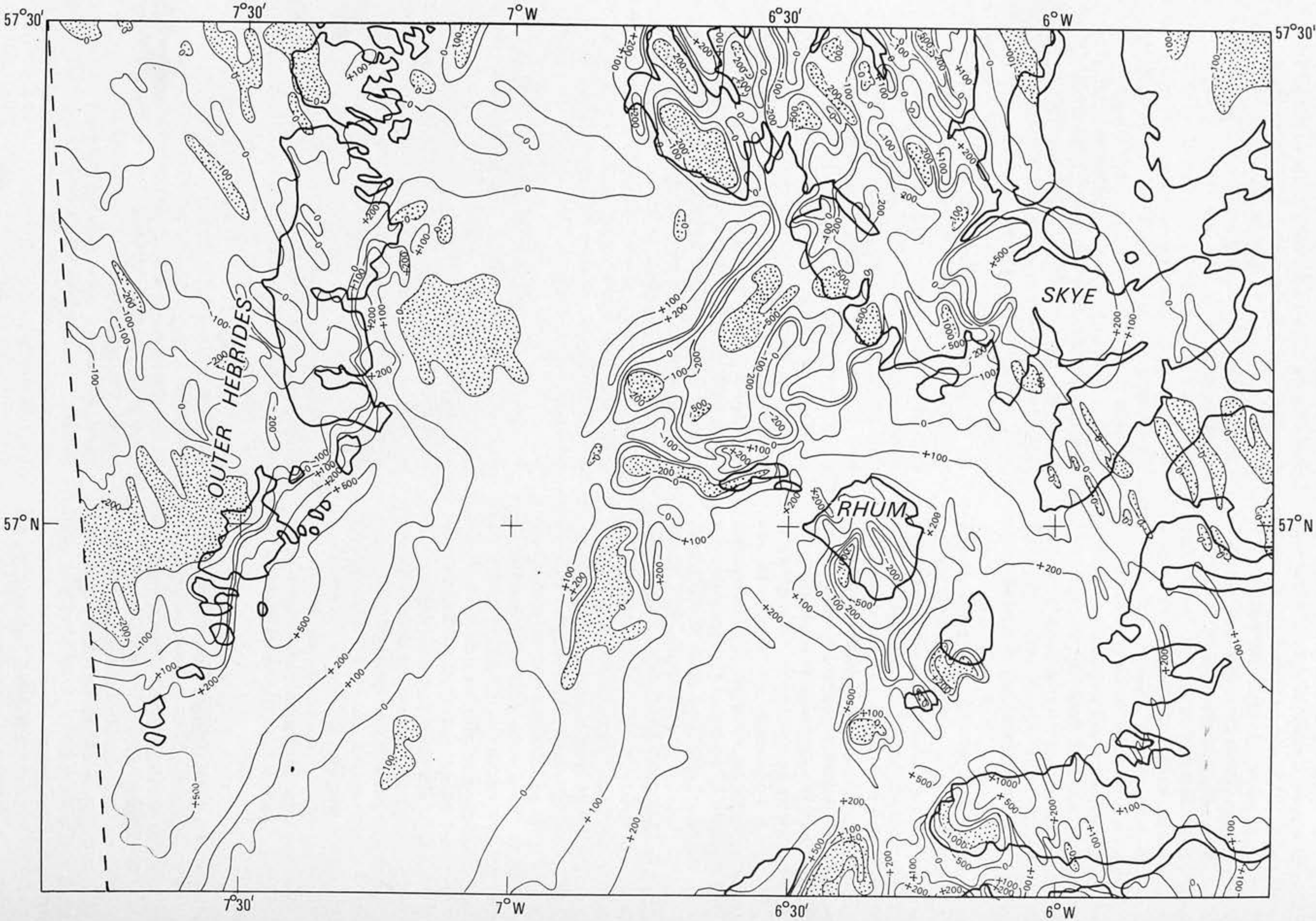


Fig. 4a. Aeromagnetic map of total force magnetic anomalies

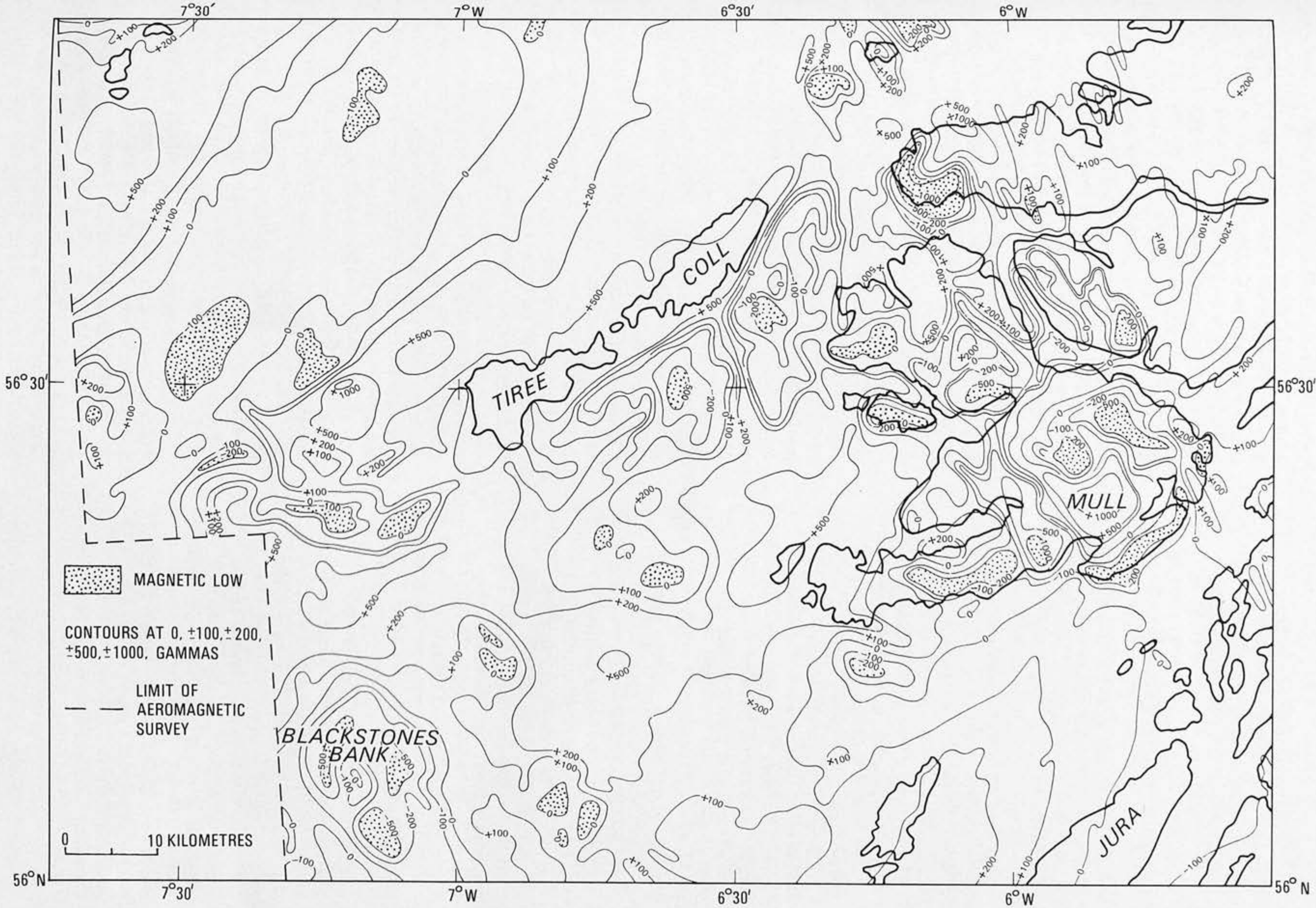


Fig. 4b. Aeromagnetic map of total force magnetic anomalies

Fortunately, other supporting evidence, both morphological and seismic, is available which will be discussed below.

Other more detailed features of the magnetic map are discussed in a later section where they have relevance to the interpretation of particular details of the pre-Quaternary geology.

*BOUGUER ANOMALY GRAVITY MAP*

The Bouguer anomaly gravity map (Fig. 5) is compiled from the results of the Institute's marine surveys in R.R.S. John Murray in 1968, and Surveyor in 1970; and from land surveys made by the Institute over a number of years. The map also incorporates data collected by McQuillin and Tuson in Rhum, Eigg and Canna (McQuillin and Tuson, 1963). All gravity values are reduced to sea level datum and referred to a value of 981.26500 $cm/s^2$ at Pendulum House, Cambridge; anomaly values indicate deviations of gravity from the theoretical field given by the 1930 International Gravity Formula (Cassinis, 1930). Bouguer corrections at sea were calculated assuming a rock density of 2.67 $g/cm^3$, whereas on land Bouguer and terrain corrections have been applied assuming a variable density related to local geology.

The gravity map, Fig. 5, forms part of a larger map which will be analysed in much greater detail in other publications. Discussion here will be limited to the contribution of gravity evidence to our interpretation of the geology (Fig. 2). It is convenient to divide the area in two, discussing first the anomalies east of 08° 00'W, where interpretations are relatively unambiguous, before discussing anomalies west of 08° 00'W, where interpretations are generally most tentative.

*Anomalies to the East of 08°00'W.*

The geology of the area east of 08° 00'W is well resolved and the gravity anomaly pattern is in all major respects understood. Areas of high gravity or local maxima, gravity highs, are related to crustal bodies of higher than average density. Conversely, areas of low gravity or local minima, gravity lows, are related to bodies of lower than average density.

In the present area, gravity highs relate to high density basement ridges or structural blocks, in which case the anomalies are usually elongated parallel to a major structural trend; or they relate to high density intrusive bodies within Tertiary volcanic centres, in which case they are nearly circular.

The occurrence of large positive gravity anomalies over the Hebridean Tertiary centres was first discovered by Tuson (1959) in Skye, Ardnamurchan and Mull. He showed that these were best explained by postulating beneath each centre a basic or ultrabasic intrusive body with density of about 3.0 $g/cm^3$ whose space form approximates closely to that of a vertical cylinder. This work was followed by a survey of the Rhum centre by McQuillin and Tuson (1963) where an even larger anomaly was discovered, and in this case the authors favoured a truncated cone space form and a density of about 3.1 $g/cm^3$. The present work confirms the near-circular shape of the Rhum and Ardnamurchan anomalies where these extend offshore and provides new evidence on the Blackstones anomaly, previously noted by Roberts (1970) from results of a Hydrographic Department survey. This discovery of a large positive anomaly over the Blackstones Bank confirms Bullerwell's (1963, p. 67) suggestion, from aeromagnetic evidence that a large Tertiary volcanic centre underlies this bank. Indeed, the anomaly here is larger than any of the other Hebridean centres, even when a higher background gravity field is allowed for. A preliminary interpretation indicates that the causal body can be approximately represented as a cylindrical mass, density 3.1 $g/cm^3$, radius 5 km, vertical height 16 km, though for exact fit, certain modification to this simple model will be necessary. Nevertheless, the simple interpretation is sufficient to show that this intrusion is probably very similar to the Rhum complex where a similar high density was required to explain the anomaly and where the causal body was shown to extend into the lower crust below the point where further contrast in density would be expected. Samples collected from Blackstones Bank, are, as expected, of basic igneous rock . The limits of the Blackstones Complex, as mapped here, are interpreted from shipborne magnetic profiles and sea-bed topography, and enclose an area entirely within the circumference of the cylinder interpreted from the gravity evidence. By analogy with other Hebridean Tertiary centres, the gravity evidence would suggest that the complex should be exposed over an approximately circular area, nearly twice as large as presently mapped, and the area shown in the present geological map represents a minimum likely size.

Gravity highs over high density basement ridges have in general a Caledonoid trend ranging from north-north-east to north-east. These have pronounced correlation with belts of positive magnetic anomaly. Three main belts of high gravity exist, each with local subsidiary features relating to secondary geological structures; for present purposes we will call these the Outer Hebrides High, the Tiree/Stanton Banks High and the Iona High.

The Outer Hebrides High is an elongate gravity ridge with values generally greater than +60 mgal, which can be traced throughout the length of the Outer Hebrides, and on the map, Fig. 5, is traced from the east coast of Benbecula southwards along the east coast of South Uist, turning south-westwards through Barra to Berneray and continuing on this trend for a further 60 km. The trend of this anomaly is sharply transverse to regional foliation trends in the metamorphic basement. Gradients eastwards from the axis of this feature of high gravity gradient mark the line of the southern end of the Minch Fault. This linear gravity feature dies out about 30 km north of the Stanton Banks where Mesozoic rocks form a south-west terminating wedge against the Minch Fault. Gravity data provide no evidence for any major south-westerly extension of the fault beyond this area. The high gravity zone is for the most part related to high density rocks generally to the east of the Outer Isles Thrust; but the line of the thrust is not marked by steep gradients, and, north of the present area in Lewis, a gravity low is seen to extend across the thrust plane without deflection. Furthermore, some regions mapped as being structurally below the thrust plane have high gravity over them. Inspection reveals a correlation between high gravity and the occurrence of gneisses described as pyroxene-granulites and associated rocks. These have been described by Dearnley (1962) from localities structurally above the thrust plane in Benbecula and South Uist, and recent work in north Barra and the islands of the Sound of Barra (Francis, in press) has revealed an extensive occurrence of granulites in a locality below the thrust plane well correlated with a local gravity maximum (Fig. 5). Thus, it appears that major zones of contrasting density exist in the Lewisian of the Outer Hebridean area; the belt of high gravity being associated with an extensive zone of high density granulites which runs, mainly offshore, along the eastern margin of the island group. The Outer Isles thrust has in places carried a wedge of these granulites westwards into their presently exposed position, though displacement along this thrust is not necessarily more than a few kilometres. The general westward lowering of gravity across the Outer Hebrides relates to a parallel belt of lower density gneiss, the grey gneisses, which are in places injected by granites.

The Tiree/Stanton Banks High, though similarly related to high density basement, is neither as extensive nor as simple a feature as the Outer Hebrides High, partly because it includes areas of subsidiary low gravity, and partly because it merges with the large Blackstones High. Interpretation is complicated by the fact that much of the anomaly is over unsampled sea floor, particularly the areas of highest gravity. From the present sparse knowledge it is not possible to say whether the higher gravity areas relate to basic intrusions within Lewisian paragneiss or to masses of basic granulite as in the Outer Hebrides. Subsidiary gravity lows probably relate to bodies of grey orthogneiss or granitised gneiss; samples of Lewisian granite from the Stanton Banks are from a relatively low gravity locality. A well developed subsidiary low north-west of Skerryvore may have a similar origin. The general area of the main feature includes a belt of Torridonian rocks along its north-west margin, and the subsidiary gravity trough north-west of the Blackstones Bank probably relates to a down-faulted block of Torridonian within the Lewisian. Northwards from Coll a weak gravity ridge runs north-north-east through Rhum and Skye into Raasay, marking a continuous ridge of Torridonian and Lewisian rocks flanked on both sides by Mesozoic basins. Gradients along the flanks of the Tiree/Stanton Banks High are generally weak, except along the south-westerly flank between the northern end of Coll and Skerryvore. Along this line a well developed gravity feature almost certainly has a similar origin to that over the Minch Fault. Therefore, a major fault between Lewisian and Mesozoic rocks is postulated. Other geophysical and geological evidence combine to support the interpretation that this is the south-westerly extension of the Camasunary Fault (Fig. 2).

The Iona High is a relatively weak feature. Aeromagnetic evidence indicates that Lewisian rocks have only limited offshore extension within a larger area of Torridonian rocks, and magnetic and gravity evidence suggests that this Torridonian cover is probably relatively thin over much of its outcrop.

Having discussed the geological interpretation of the various gravity highs, discussion of the gravity lows remains. Two main belts of gravity low are identified; one we shall call the Sea of the Hebrides Low, the other we shall treat as two anomalies, the Treshnish Low and the Eigg Low, though these are part of the same belt of low gravity which is straddled by the Ardnamurchan Gravity High.

The Sea of the Hebrides Low is associated with the largest of the Hebridean sedimentary troughs containing Mesozoic rocks, underlain by an unknown thickness of Palaeozoic and Pre-cambrian sedimentary rocks. Although most of our detailed knowledge of this trough is derived from seismic and sampling data, the gravity map is important in indicating how the structure includes a northward continuation of thick sedi-mentary rocks beneath the lavas of the Canna Ridge and North Skye. A linear feature of moderate gradient runs from 10 km west of Barra Island to Idrigill Point on Skye (near sample site SH 119, Fig. 2). Deep seismic lines are poorly placed to investigate this anomaly, but the south-western end is seen on one of the sections and a considerable thickening of Mesozoic sediment is indicated. However, the structure is not seen on seismic lines nearer Skye, and the gravity effect is probably partly associated with a sub-Mesozoic structural line.

The Treshnish Low is analogous to the low over the Canna Ridge. The presence of small Mesozoic outcrops beneath the lavas on north-west Mull, together with the topographic depression south of the Treshnish Isles, indicate this low also is caused by a Mesozoic trough, fault bounded to the north-west by the Camasunary-Skerryvore Fault. The gravity data indicates that the trough has an asymmetric sectional form, probably having an unconformable south-eastern boundary, Mesozoic rocks overlying Moine metamorphic basement. Although not of large areal extent, this trough is probably as deep as the Sea of the Hebrides trough. No deep seismic profile is available, but the gravity anomaly is consistent with there being about 3 km of Mesozoic rocks against the south-east flank of the boundary fault. However, older sedimentary rocks of higher density may also provide infill, in which case the required Mesozoic thickness is smaller, but the total depth to Lewisian basement is consequently greater.

The Eigg Gravity Low is related to a northward extension of the Treshnish Low, interrupted by the Ardnamurchan High. The Eigg Low is probably associated with a further local thickening of the Mesozoic rocks against the Camasunary-Skerryvore Fault, but here the complexities of the gravity field, caused by interfering anomalies, are such that interpretation is impracticable.

An area of low gravity not yet fully investigated is that between Colonsay and Dubh Artach islet (Figs. 2 and 5). A deep reflection profile indicates that Mesozoic rocks probably occur in a shallow trough extending both sides of the Great Glen Fault, but gravity coverage here is incomplete and the geology of this area is in many respects unresolved.

*Anomalies to the West of 08°00′W.*

East of the Minch Fault a sequence of young sediments drapes over the older rocks, thickening westwards towards the edge of the continental shelf and over the continental slope. Beyond 08° 30'W, shallow seismic records give only a few poor indications of rockhead reflections from beneath this sediment layer, and no samples of consolidated rock have been obtained west of 08° 00'W. Thus our knowledge of the geology is poor and interpretations are tentative.

Gravity evidence is the basis of our suggestion that a complex asymmetric trough of Mesozoic sedimentary rocks is probably present to the east of the Outer Hebrides ridge. A sublinear high gradient gravity feature appears to mark the western limit of the Outer Hebrides Lewisian ridge, approximately along the 08° 00'W meridian. This gravity gradient coincides with a well defined topographic feature and magnetic, morphological and seismic character all change on crossing this boundary. This line is interpreted here as the faulted eastern margin of the trough which thins westwards towards a poorly defined unconformable boundary. Structure in this trough may be complex, the main gravity anomaly being marked by a number of subsidiary features, but not enough control data is yet available for a more detailed analysis.

Other features of the gravity map beyond the margins of this trough may be related either to inhomogeneities in the basement or to buried topography beneath the draping sediment layer. Further seismic work using a deeper penetration system is required to resolve such features of the geology and resolve uncertainties in the gravity interpretation.

## *SHALLOW REFLECTION AND SHIPBORNE MAGNETOMETER RESULTS*

Shipborne magnetometer results are not used to produce a magnetic anomaly map, the aeromagnetic map being already available; however, the magnetograms have a valuable interpretative function when used in conjunction with shallow reflection seismic profiles. Precise relationships between magnetic anomalies and structural features can be studied and the position of faults, dykes, geological boundaries, sills etc. accurately located. The results are also used in mapping and identifying geophysical domains.

Shallow seismic profiles have a further important function. From them, it is possible to interpret the thickness of a top seismic layer, the Quaternary sediment layer.

Selected shallow seismic and magnetometer profiles are indicated on Fig. 2 and drawn in Figs. 7-10.

## *DEPTH TO ROCKHEAD AND SEDIMENT ISOPACHYTE MAP*

A major acoustic reflector, coinciding with a stratigraphic unconformity, occurs throughout the area and has been interpreted as a rockhead reflection. On the inner shelf the layer above this reflection is interpreted as Quaternary sediments. The thickness of this layer has been calculated assuming a seismic velocity of 1.8 km/s; isopachytes are shown in Fig. 6. Depths to the

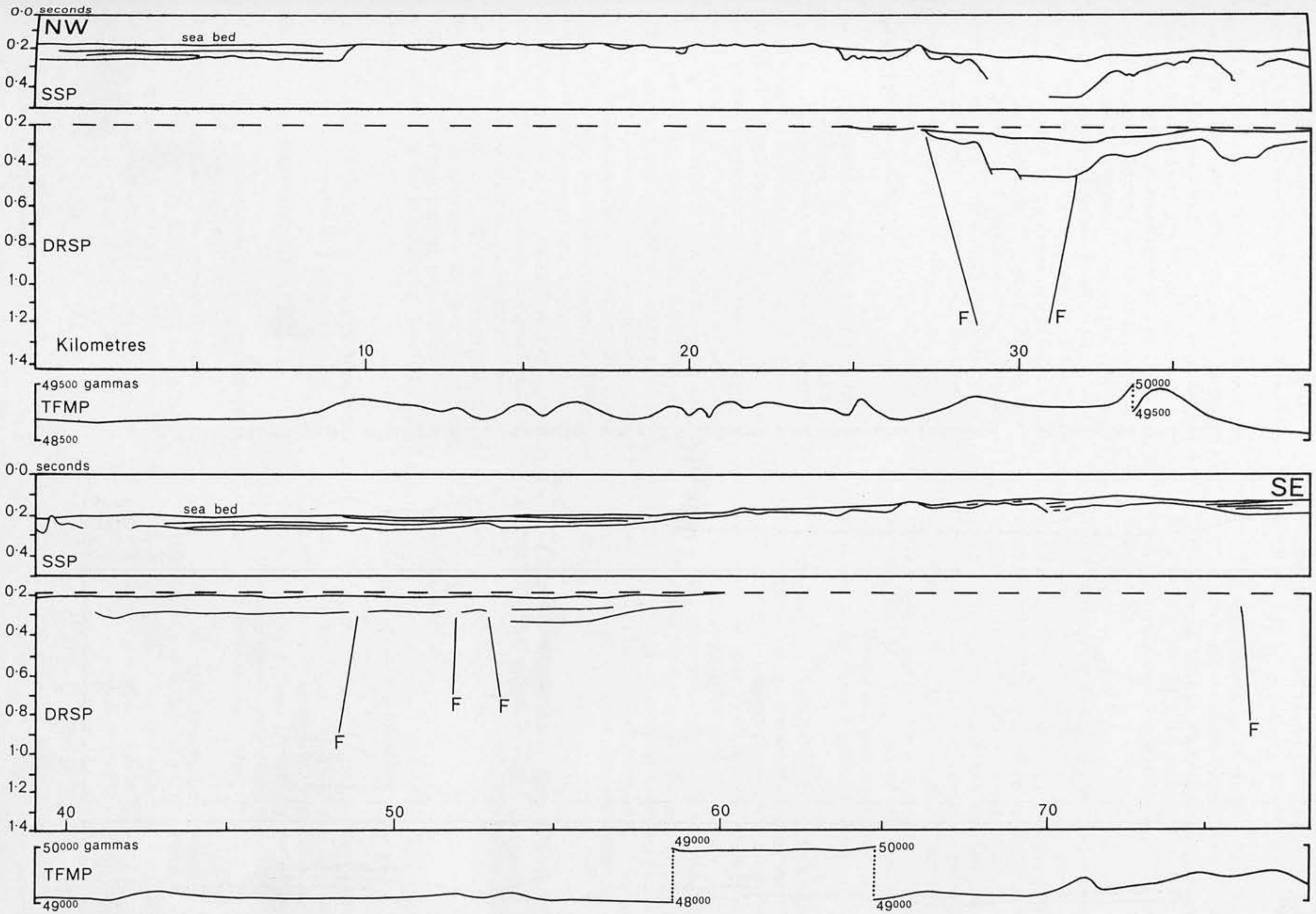


Fig. 7a. Section A-A': shallow and deep reflection and shipborne magnetometer profiles. For location see Fig. 2

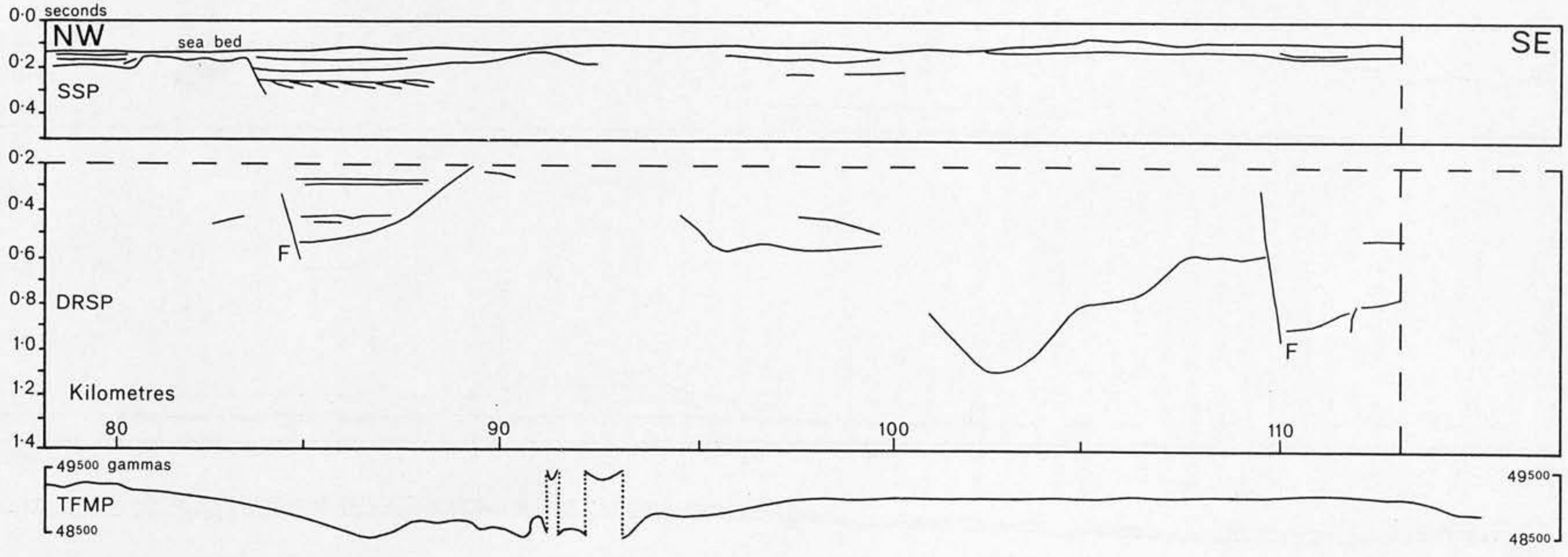


Fig. 7b. Section A-A': shallow and deep reflection and shipborne magnetometer profiles. For location see Fig. 2

rockhead reflector are calculated by adding water depth to sediment thickness and interpolation of isobaths between reflection profiles is based on the denser cover of bathymetric data. Isobath contours are shown in Fig. 2.

In the Sea of the Hebrides channel and around the Inner Hebrides, rockhead is an obviously glaciated surface; but on the outer shelf, no large scale glacial erosion forms are evident, and the possibility that Tertiary sediments form part of the uppermost seismic layer cannot be excluded. However, the rugged surface of Stanton Banks, known to be glaciated (Eden and others, 1971, p. 28), and the shoals south of the Outer Hebrides can be traced for appreciable distances beneath the sediment cover, and furthermore, calculated thicknesses of sediment are consistent with this being entirely the product of erosion during Pleistocene glaciations.

### *GEOPHYSICAL DOMAINS*

Our interpretation of the geology beneath the uppermost layer of Quaternary sediment is based on seismic, magnetic, gravity and morphological evidence, controlled by sample identification and observation of the relationships between offshore and onshore geology. The method is partly subjective, in particular in the interpretation of shallow seismic sections where the ability to recognise those characteristic features which relate to a particular group of rocks is mainly acquired through experience rather than observation of a formal diagnostic method. Rock group classification is attempted in terms of geophysical characteristics, then the area is mapped as a mosaic of geophysical domains; within any domain the geophysical records have consistent characteristics and domains of similar geophysical character are interpreted to be geologically similar. Geological identification of the rock group associated with each type of domain is wherever possible based on sampling evidence.

The rocks of the Sea of the Hebrides have been grouped as shown in Table 1.

### *DEEP SEISMIC REFLECTION RESULTS*

Two main seismic reflectors have been identified in a complex and extensive asymmetric sedimentary trough which is bounded to the west by the Minch Fault and to the east by, for the most part, an unconformable boundary against Palaeozoic or Precambrian basement (Fig. 2 and sections, Figs. 7-10).

The upper reflector, horizon A, is deepest north-westwards from Coll, where a maximum two-way time of 995 ms is recorded. Other isochron lows of 700-800 ms are recorded in other parts of the trough. This horizon, A, crops out near the margin of the trough north-westwards of Coll, but to date no sample has been obtained.

A deeper horizon, B, is deepest off the south-west coast of Skye in an area where refraction as well as reflection measurements have been made (Smythe and others, 1972) and where a maximum two-way time of 1620 ms is recorded.

The interval A-B reaches values exceeding 1050 ms in the trough eastwards from Barra, and 1300 ms south-westwards from Skye. Velocities determined during the reflection survey vary between 2.5 and 3.5 km/s in the rocks above horizon B, without any sharp discontinuity being detected. IGS refraction measurements (Smythe and others, 1972) give a value of between 3.0 and 3.9 km/s for the same interval. Thus it is deduced that the thickness of infill, most likely of New Red Sandstone and younger rocks, reaches a maximum of about 3 km near Skye.

At deeper levels in the seismic sections, weak reflections are seen which probably relate to deep horizons in the Torridonian sandstone sequence, or may even mark in places the base of this sequence over metamorphic rock; reflections are, however, not easily correlated between profiles and the main significance of this data is that it provides supporting evidence for the proposition that throughout most of the trough a thick layer of Torridonian sandstone underlies the younger infill.

The seismic sections indicated on Fig. 2 are shown in Figs. 7-9.

## Geological Results

### *SOLID GEOLOGY*

#### *Sampling Methods and Problems*

Although sea floor exposure is common and often extensive (Fig. 11; Eden and others, 1971) the rock exposed is mostly crystalline and worn smooth by glaciation. Mesozoic sediments, having been eroded, now floor depressions filled with unconsolidated material.

Early attempts at sampling, using a dredge, yielded only erratics with no single rock type predominating. Recoveries using a gravity corer fitted with a heavy steel barrel were poor and the possibility that the corer had hit a boulder could not be discounted. The gravity corer samples described in the next section lay beneath a thin cover of superficial sediment and are of friable rock, unlikely to have survived glacial transport. Although there is some doubt

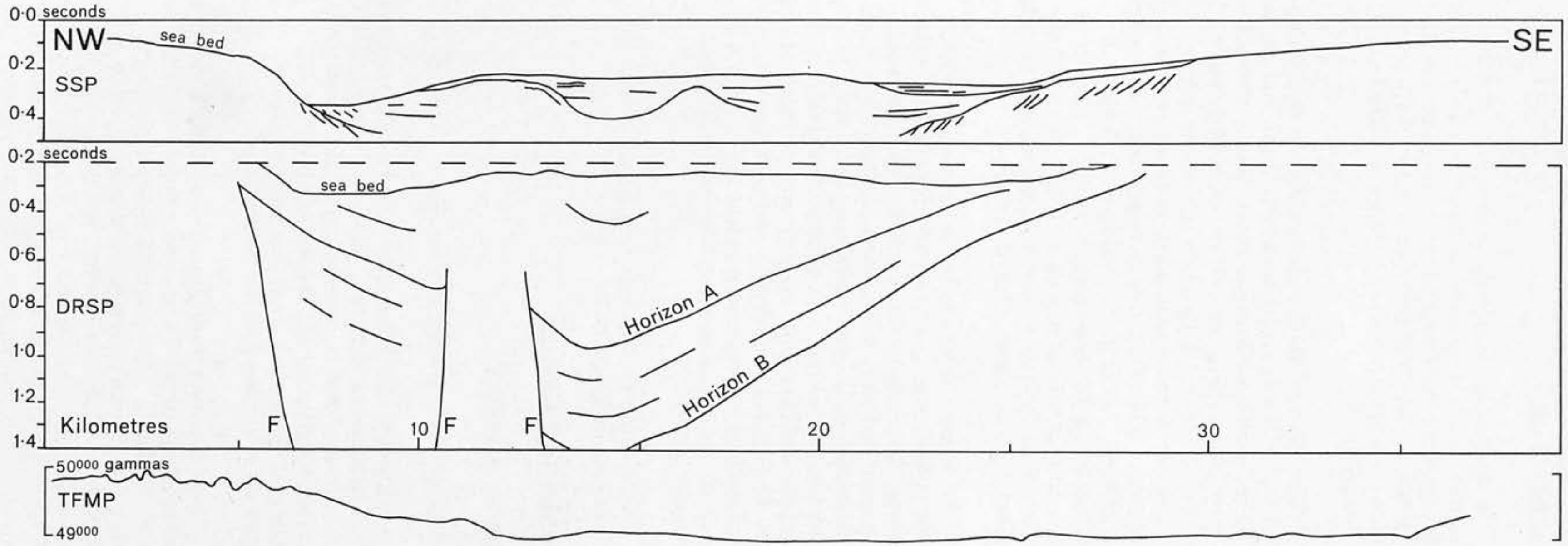


Fig. 8. Section B-B': shallow and deep reflection and shipborne magnetometer profiles. For location see Fig. 2

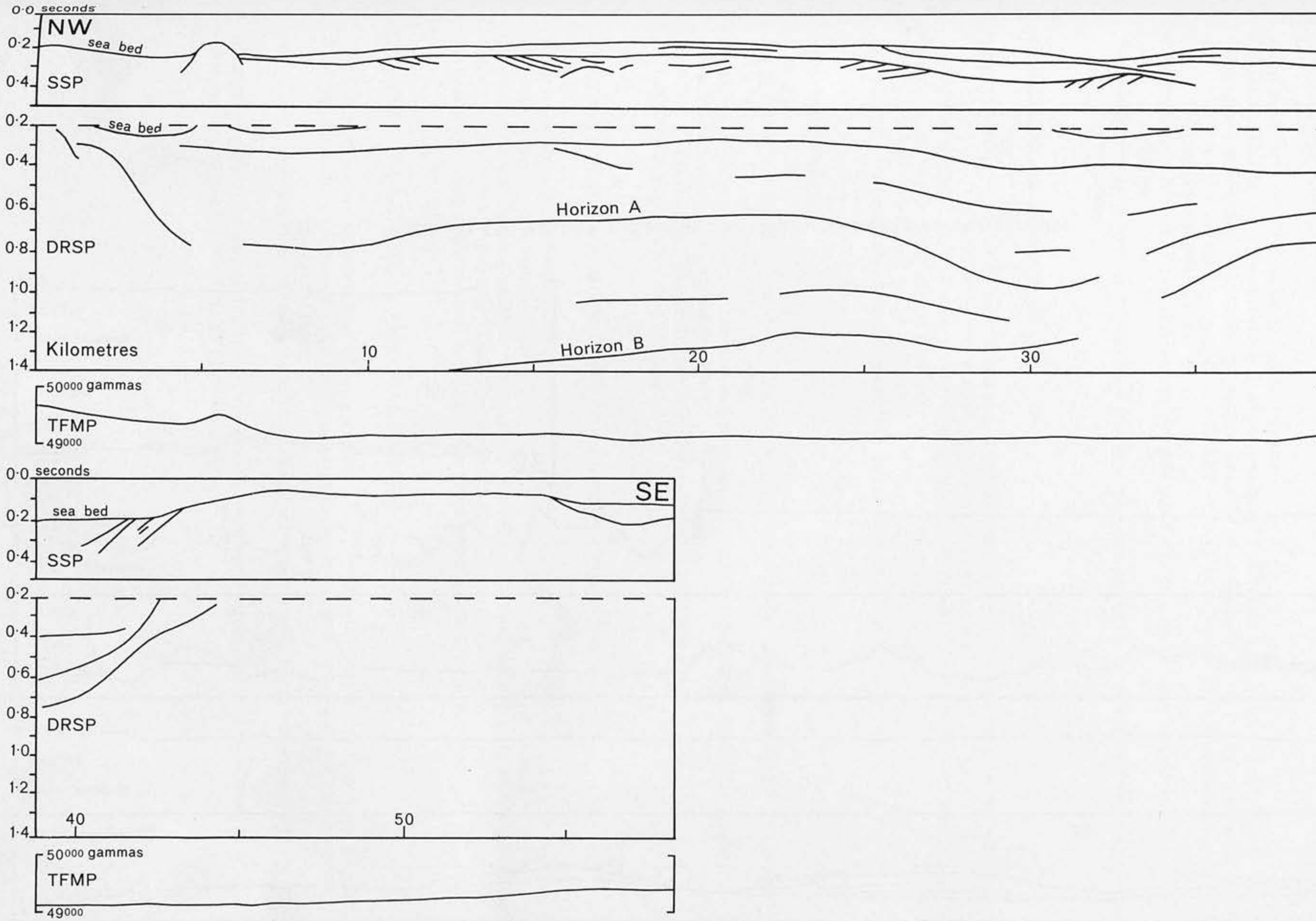


Fig. 9. Section C-C': shallow and deep reflection and shipborne magnetometer profiles. For location see Fig. 2

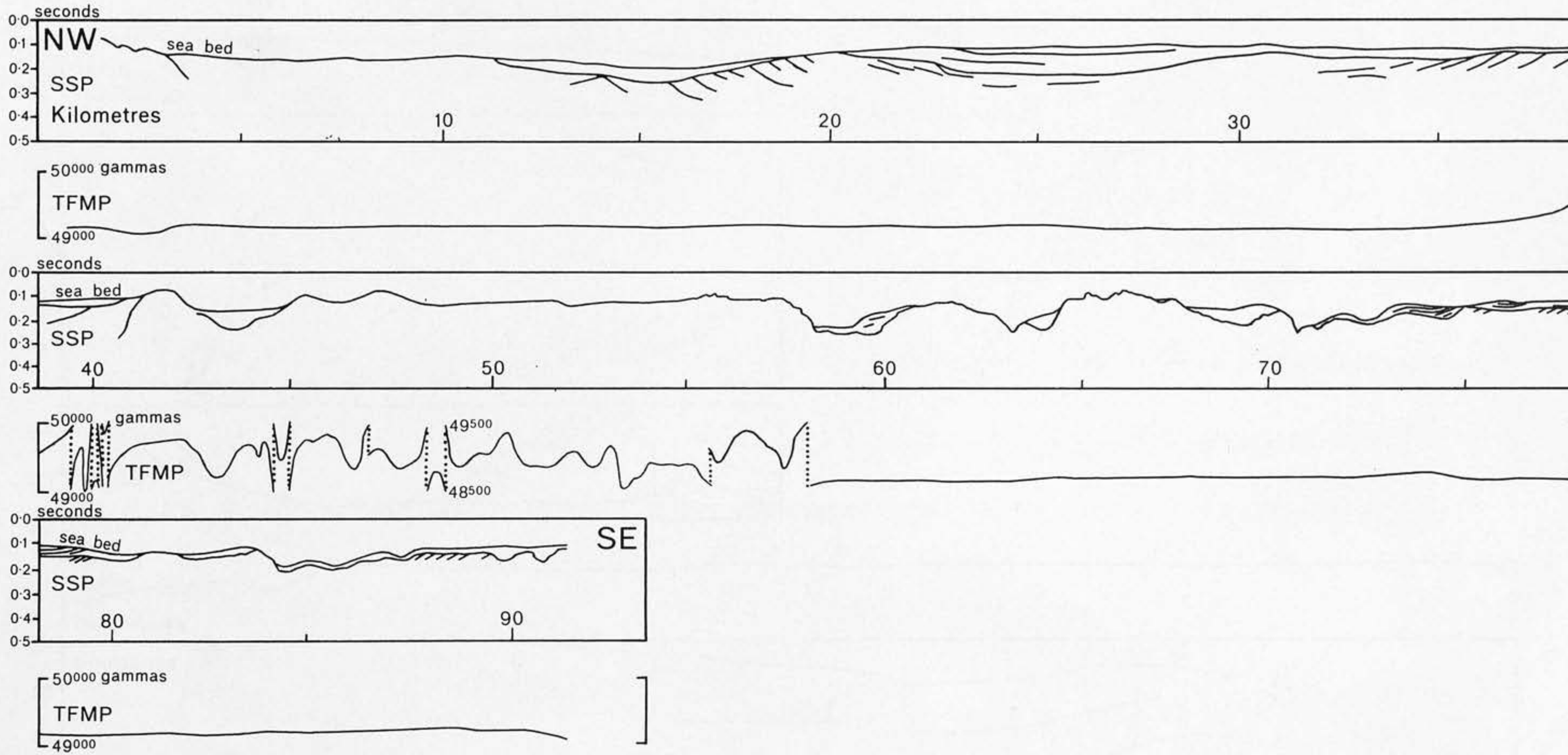


Fig. 10. Section D-D': shallow reflection and shipborne magnetometer profiles

Table 1. Rocks of the Sea of the Hebrides

PRECAMBRIAN GNEISSES

Deep seismic - no reflections, high velocities
Shallow seismic - no penetration, many hyperbolic reflections from top surface
Magnetic - moderate amplitude anomalies usually of large wavelength compared with depth to top surface. Larger anomalies usually over areas of paragneisses and/or pyroxene granulites
Gravity - usually high, but subsidiary gravity lows occur usually associated with granitised bodies
Morphology - very uneven surface on sea bed or when covered by sediments or sedimentary rocks

PRECAMBRIAN AND PALAEOZOIC ROCKS

Deep seismic - generally no reflections, high velocities; some questionable reflections deep in the Torridonian or from the base of the Torridonian
Shallow seismic - no reflections from depth but a few hyperbolic reflections from top surface
Magnetic - weak anomalies in places
Gravity - near mean anomaly values
Morphology - resistant; scarps appear to be present in places

MESOZOIC ROCKS

Deep seismic - good reflections, moderate to low velocities, good penetration in bedded sequence of reflectors
Shallow seismic - good penetration and resolution of rock structure; bedding and faults
Magnetic - anomalies generally absent
Gravity - usually low, in particular over deep troughs of these rocks
Morphology - smooth eroded top surface

TERTIARY PLUTONIC ROCKS OF THE CENTRAL COMPLEXES

Deep seismic - no penetration
Shallow seismic - no penetration
Magnetic - very large amplitude anomalies, arcuate patterns, moderately large wavelengths
Gravity - very large gravity highs, nearly circular anomaly patterns
Morphology - resistant to erosion; structureless shoals are characteristic

TERTIARY LAVAS AND HYPABYSSAL ROCKS

Deep seismic - no penetration, strong reflections if rock enclosed in sedimentary sequences
Shallow seismic - no penetration, strong reflections from surface, dyke patterns very characteristic
Magnetic - moderate to large anomalies usually of short wavelength; uneven anomaly pattern
Gravity - generally not of sufficient volume to cause perceptible gravity anomalies at sea
Morphology - similar to that of plutonic rocks

about the status of these samples they form, together with the geophysical records, contributory evidence for the interpretation advanced in this account.

More successful in recovering solid rock from glaciated surfaces have been light, cable-controlled drills with mounted underwater television camera. During development, the Harrison Drill (Eden and others, 1970) and the IGS Midi Drill (Eden and Ardus, 1972) have both recovered samples.

Five samples have been taken by the submersible Vickers Pisces; three using a manipulating arm or claw to pick out weathered-out blocks and two using a Harrison Drill attached to a torpedo-recovery claw (Eden and others, 1971, 1973).

In water up to 35 m deep, particularly where rock exposure is rugged, Scuba diving has proved the quickest and surest method of recovering samples. The procedure has been for the shoal to be located and buoyed, and for divers, attended by an inflatable dinghy, to descend the buoy rope and recover samples.

Two boreholes have been drilled by m.v. Whitethorn to recover cores of sedimentary rock lying beneath drift (Chesher and others, 1972) and a further programme is planned.

*Descriptions of Samples*

Numbers prefixed by 'SH' refer to the sample collection of Continental Shelf Unit II, those prefixed by 'CSA' are preparation numbers of CSU II and the Institute's Palaeontology Department; those prefixed by 'C' refer to the Institute's sliced rock collection. All solid rock sample stations are indicated on Fig. 2.

SH 28 (C 44) 2.8 km east-south-east of Chathastial Light, off Eigg Island, Inner Hebrides. Lat. 56° 52' N Long. 06° 05' W

A sample taken by divers from a flat rock surface. Two sets of vertical joints were observed, one trending north-west and the other west-north-west.

The rock is a coarsely ophitic olivine-basalt containing pseudomorphs after anhedral crystals of olivine, small laths of zoned labradorite ($An_{60}$ at core) rimmed by oligoclase, large ophitic plates of pale brown augite and plates of iron ore. Interstitial and amygdaloidal patches occur filled by analcime, a massive zeolite, carbonate and chloritic material. The olivines are replaced by pseudomorphs of a dense brownish fibrous aggregate, probably mainly oxidised bowlingite; they have a subophitic or ophitic relationship to the feldspar and tend to be concentrated in patches. Locally the rock is somewhat chloritised.

The petrology of the rock and its proximity to the igneous rocks of Eigg indicate that it is of Tertiary age. R.W.E.

SH 119 (C 125) 2.8 km south of Idrigill Point, West Skye. Lat. 57° 18' 30" N Long. 06° 35' 20" W

A Harrison Drill core from a glaciated pavement.

An ophitic olivine-basalt containing numerous small crystals of olivine, locally replaced by oxidised serpentinous material, small laths of labradorite, coarse ophitic plates of faintly purplish augite and small plates or iron ore. Chloritic material fills sparse interstitial patches and also, locally, slightly replaces the plagioclase. Rare small patches of analcime occur. A single phenocryst of labradorite is present in thin section.

The petrology of the rock and its proximity to the lavas of Skye indicate that it is of Tertiary age. R.W.E.

SH 133 (CSA29) 4.3 km south-east of Barra Island, Outer Hebrides. Lat. 56° 20' N Long. 07° 21' W

A rock corer sample from the base of a glaciated trough. Some doubt exists as to the status of this sample as it was taken by a gravity corer. Shallow seismic profiling however indicated outcrop and the sample appears too weak to survive glacial transport.

The sample is of a light grey, fissile shale with some fine grained shell fragments. A very small fine sand fraction contains quartz, biotite and a white mica, the two micas giving the sample a moderate fissility. There are abundant microfossils (Appendix 1) but the composition of the assemblage is such that it is not possible to date it more precisely than Jurassic to Lower Cretaceous.

SH 166 (CSA 30) 2 km north of Ockle Point, Ardnamurchan. Lat. 56° 47' N Long. 06° 03' W

A gravity corer sample. The corer passed through 0.80 m of modern and late glacial sediments before coring the sample. The rock is extremely friable and would be unlikely to survive glacial transport.

The sample is of a fine grained, massive, grey, calcareous sandstone. Microfossils (Appendix 1) indicate a Liassic to early late Jurassic age. This identification is consistent with the presence of strata of this age on Ardnamurchan.

SH 175 (C 129) 9 km south-east of Eriskay Island, Outer Hebrides. Lat. 57° 00' N Long. 07° 11' W

A gravity corer sample from a shoal area.

A decomposed ?tuff containing rounded, subangular and some very angular quartz grains (commonly about 0.15 mm in diameter) with decomposed feldspar, muscovite, altered biotite and granular iron ore in an argillaceous matrix. A few patches of greenish clay mineral may represent altered volcanic glass. Some of the quartz grains have a delicate sliver-like form. R. W. E.

SH 177 (CSA 40) 9 km east-south-east of Barra Island, Outer Hebrides. Lat. 56° 55' N Long. 07° 18' W

A gravity corer sample. The corer passed through 1.5 m of recent mud down into a yellowish compact sand (0.08 m) which graded into a friable white sand. It is unlikely that this rock could have survived glacial transport.

The white sand is medium grained and well sorted. It consists almost entirely of quartz grains with traces of a calcareous cement. Most grains are angular or subangular but some have a high roundness and sphericity index.

No microfossils were found in the sample; however the lithology (and in particular the presence of well rounded quartz grains) strongly resembles that of Upper Cretaceous strata of Mull and Morven (Lee and Bailey, 1925, p. 115).

SH 206 (CSA 34) 4 km east of Benbecula, Outer Hebrides. Lat. 57° 25' 25'' N Long. 07° 08' 00'' W

A gravity corer sample. The corer passed through 0.45 m of modern mud overlying the sample which contains fissures filled with the mud. The rock is extremely friable and would be unlikely to survive glacial transport.

A white sandy limestone. The sand fraction consists almost entirely of clear angular, medium to fine grained quartz fragments with a small amount of hornblende. The microfossil assemblage (Appendix 1) found in the specimen indicates a late Rhaetian or early Hettangian age.

SH 207 (CSA 33) 4 km east of Benbecula, Outer Hebrides. Lat. 57° 25' 00'' N Long. 07° 08' 00'' W

A gravity corer sample. Recent mud, 0.05 m thick, covered the sample, which consisted of light red mudstone containing a late Permian microfossil assemblage (Appendix 1).

SH 216 (C 204) The north-west corner of Stanton Banks. Lat. 56° 15' N Long. 07° 56' W

A loose block of solid rock picked out by the claw of Vickers Pisces.

The sample is very coarse, pale red microcline-granite composed of subhedral to anhedral plates of perthitic microcline (locally as phenocrysts), albite-oligoclase, quartz, olive-green biotite and rare plates of bluish-green hornblende. Accessory minerals include zircon, sphene, apatite and iron ore. Myrmekitic blebs of quartz occur in the plagioclase. The perthitic intergrowths are of stringlet type. The quartz shows undulose strain extinction and granulitisation is commonly developed at the margins of large patches of quartz. In hand specimen a phenocryst of microcline 20 mm long was observed (see also SH 217, below). R. W. E.

SH 217 (C 205) The north-west corner of Stanton Banks. Lat. 56° 16' N Long. 07° 55' W

A loose block of solid rock picked out by the claw of Vickers Pisces.

A reddish microcline-granite very similar to SH 216. Hornblende, however, was not observed in thin section and the perthitic structure is more variable and types observed are of the stringlet, string and bead types. As in SH 216 the areas of quartz show undulose strain extinction and granulitisation at the margins of patches. A number of thin anastomosing lines of granulation traverse the rock.

These two specimens (SH 216 and SH 217) from Stanton Banks are similar to Lewisian (Late Laxfordian) granitic rocks. Sliced specimens of rocks of this suite from the Outer Hebrides are extensively affected by cataclasis but otherwise bear strong resemblance to these specimens. R.W.E.

SH 221 (C 206) 4 km south-south-west of Canna. Lat. 57° 01' N Long. 06° 35' W

A sample taken by divers from a large area of glaciated rock.

An ophitic olivine-basalt composed of a plexus of laths (commonly 0.3 to 0.5 mm long) of bytownite zoned to labradorite, large ophitic plates of pale purple augite, pseudomorphs in brownish fibrous material after olivine and small plates of iron ore. Pale brownish material of moderate birefringence, possibly a mineral allied to montmorillonite, occurs, locally with carbonate in amygdaloidal and interstitial patches.

The petrology of this specimen together with its proximity to the lavas of Canna indicate that it is of Tertiary age. R.W.E.

SH 223 (C 207) The Sound of Sleat. Lat. 57° 01' N Long. 05° 53' W

A loose block recovered with the claw of Vickers Pisces from the top of a steep rock shoal from which the block was almost certainly eroded.

An ophitic dolerite composed of laths of bytownite zoned out to about labradorite, large ophitic plates of pale brownish augite and plates of iron ore.

The petrology and field relations (Eden and others, 1971) of this specimen suggests that it is from a Tertiary intrusion. R.W.E.

SH 226 (C 208) 10 km west-south-west of Muck Island. Lat. 56° 44' N Long. 06° 25' W

A core taken with the Harrison Drill fitted to Vickers Pisces.

A fine grained red arkose composed of subangular and subrounded grains. The main minerals are quartz, and numerous grains of feldspar, including microcline, orthoclase, microperthite and albite. A few flakes of muscovite and biotite are present. Clay minerals, probably mainly clay mica with some chlorite occur along the margins of the detrital grains and in interstitial patches. Small interstitial patches of kaolinite and also of carbonate occur. Accessory minerals include iron ore, leucoxene, zircon and sphene locally concentrated in very thin bands.

The petrology of this specimen, indicates that it is Torridonian in age. R.W.E.

SH 237 6 km east of Colonsay Lat. 56° 06' N Long. 06° 04' W

A sample taken by divers from a steep rock shoal.

A fine grained basalt of ?Tertiary age.

SH 579 (C 217) Blackstones Bank, 40 km south of Tiree. Lat. 56° 05' N Long. 07° 10' W

A core taken with the Harrison Drill fitted to Vickers Pisces.

A gabbro composed of stout laths, up to about 2.5 mm long, of strongly zoned labrodorite ($An_{68}$ at core), subhedral to anhedral plates of pale clinopyroxene, and small plates of iron ore. Three subhedral prisms of orthopyroxene occur and oligoclase is present interstitially. Pale green hornblende occurs locally mantling and apparently replacing the pyroxene.

The petrology of this specimen together with the gravity evidence shows that it is from a Tertiary plutonic centre (see also SH 776, below). R.W.E.

SH 725 (C 227) 4 km north-east of Skerryvore Lighthouse. Lat. 56° 21' N Long. 07° 04' W

A sample taken by divers from a rock pavement.

A dark greenish diopside-scapolite-rock composed of coarse plates of green diopside concentrated in irregular folia with plates of calcic scapolite locally extensively replaced by a fine grained aggregate of carbonate and white mica. Sphene is a common accessory mineral and apatite and iron ore are also present. Locally patches of pale, optically positive amphibole and aggregates of epidote occur. One more leucocratic band is composed of oligoclase, pale amphibole, epidote and sphene.

The rock resembles a sliced rock (S' 21398) from the Lewisian of Tiree described by Richey and Thomas (1930, p. 13) as 'from the dark orthogneiss outcrop mapped with associated marble ... on the south shore of Gunna'. R.W.E.

SH 727 (C 228) 5 km south-east of Tiree
Lat. 56° 25' N Long. 06° 50' W

A sample taken by divers from a craggy exposure.

A crushed hornblende-pyroxene-granulite composed of anhedral plates of green hornblende and andesine-labradorite (about $An_{50}$) with subordinate smaller plates of pale green clinopyroxene and locally some quartz. The hornblende is somewhat concentrated in crude foliae. There is a finely granular matrix of the same minerals showing slight variation in composition. The plagioclase crystals show marked straining of the twin lamellae. Magnetite occurs in patches and vein-like stringers commonly margin the larger hornblendes. Some pyrites also occurs.

The petrology of the specimen indicates that it is of Lewisian age. R.W.E.

SH 767 (C 229) Hawes Bank, west of Coll
Lat. 56° 43' N Long. 06° 47' W

An IGS Midi-Drill core.

An indurated, red, Torridonian arkose similar in mineralogy to SH 226 (above) but medium grained.

SH 768 Hawes Bank, west of Coll
Lat. 56° 42' 45" N Long. 06° 47' 10" W

An IGS Midi-Drill core.

An indurated, red, Torridonian arkose similar to SH 767 above. Slightly coarser bands about 5 mm thick occur at intervals.

SH 776 (C 230) Blackstones Bank, south of Tiree. Lat. 56° 04' N
Long. 07° 08' W

A sample taken by divers from a glaciated rock surface.

A fine grained eucrite composed of subhedral to anhedral prisms of pale clinopyroxene and plates (from about 0.15 to 1.0 mm diameter) of calcic bytownite ($An_{79}$). A narrow veinlet composed of a felted aggregate of pale green amphibole cuts the rock and the pyroxene adjacent to the veinlet is replaced by amphibole.

The petrology together with the gravity evidence shows that this specimen is from a Tertiary plutonic centre (see also SH 579, above).

Borehole 71/9 (C 218, C 219, CSA 556) East of Colonsay, Inner Hebrides. Lat. 56° 04' N Long. 06° 06' W

A 4.20 m core of massive reddish sandstone with pebble and red shale horizons.

The sandstone, which is fine and even grained, is composed of angular to subrounded, clear quartz grains with minor feldspar and white mica. A thin film of iron oxide cement coats about half of the quartz grains and this, together with red interstitial iron oxide, gives the rock its colour.

Lithic granules and pebbles occur locally in the core and also form one horizon 0.60 m thick. A slide cut from this horizon shows a variety of metamorphic psammites. Fine to medium quartzite fragments, some foliated, are commonest but more pelitic rocks with white mica foliae also occur. Fragments of red shale similar to that forming distinct bands are common in the hand specimen. Coarse to fine quartz grains and interstitial iron oxides form a matrix.

Despite variation in preparation technique no organic residue was recovered from a sample of red shale. It is probable that the iron solutions which have cemented the sandstones have oxidised any organic material originally present. The lithology and degree of induration of the rock show it is of Old or New Red Sandstone age but it is not possible to identify it further with certainty.

Borehole 71/10 (CSA 555) 8½ km north of Eigg, Inner Hebrides. Lat. 57° 01' N
Long. 06° 05' W

A 2.90 m core of very fine, dark grey sandstone, locally shelly and bioturbated containing black shale partings and micritic limestone.

A composite palynological sample, made from shale specimens, yielded a poorly preserved miospore and organic-walled microplankton assemblage (Appendix 1), which only permitted a dating of Lower Jurassic to Lower Cretaceous. The macrofossils obtained (Appendix 2) however, when taken with the lithology suggest a top Lower to Middle Lias age.

## *SUPERFICIAL SEDIMENTS*

In this section, cruise and some preliminary laboratory results are presented. Detailed laboratory work is in progress in conjunction with Edinburgh University and will be reported separately.

### *Sampling and Laboratory Procedures*

Sediment stations lie on the Institute's reconnaissance geophysical grid at intervals of 5 nautical miles and also along selected traverses crossing trenches and banks at right angles to the strike of the topography. At each station surface and core samples were taken using a Shipek Grab and either a vibrocorer or gravity corer lined with transparent plastic tubing. At some stations dredges recovered erratic boulders; further samples from the Sound of Iona were taken privately by divers and donated to the Institute's collection.

During drilling from m.v. Whitethorn samples of superficial sediment were taken at vertical intervals of 2 m.

On board ship the colour of the sediment was noted by reference to the Munsell Soil Colour Chart, and the stratigraphy of the cores measured. Samples intended for geochemical work were deep frozen or preserved in a 1:1 mixture of chloroform and methanol. Selected cores and borehole material were frozen for archive purposes.

In the laboratory, the gravel (greater than 2.0 mm), sand (0.0624-2.0 mm) and mud (less than 0.0624 mm) fractions of all sea floor samples were separated by sieving, dried, weighed and classified according to Folk's (1968) classification. The sand fractions were examined with a binocular microscope.

### *The Sedimentary Sequence*

The term 'modern' refers here to sediment being deposited or reworked at present.

The evidence discussed below shows that the top seismic layer shown in Fig. 6 can be subdivided into three units. Boulder clay lying on rockhead is overlain by late glacial and postglacial muds; muds and shell sands, interpreted as modern, lie on these older muds.

### *Boulder Clay and Erratics*

Shallow seismic profiles, together with core and borehole evidence (Figs. 12-15) suggest that over much of the area boulder clay does not contribute significantly to the thickness of superficial sediment shown on Fig. 6. Appreciable thicknesses, however, may fill some overdeepened rock basins.

Cobbles and boulders obtained during dredging of submarine outcrop were dominated by material of local type, and other lithologies present were consistent with patterns of ice movement deduced from evidence on land.

No samples of the cobble spreads on the top of the continental slope have yet been recovered (Eden and others, 1971).

### *Late Glacial and Postglacial Muds*

Shallow seismic records, calibrated by borehole and core evidence, show that muds make a major contribution to the thickness of superficial deposits (Fig. 6). On shallow seismic profiles they are characterised by a series of horizontal reflectors which fade laterally. Borehole 71/10 (Fig. 12), passed through a series of these horizontal reflectors from which were recovered muds with no visible structures. Borehole 71/9 (Fig. 12) passed through a similar sequence and most superficial cores penetrated modern deposits to reach these older muds (Figs. 13-15).

The colour of the muds varies from dark grey (N4/ ) through greenish grey (5GY5/1) to bluish grey (5B5/1) and dark bluish grey (5B4/1); this contrasts with the olive grey (5Y4/2) of the modern muds. Hydrogen sulphide was evolved from cores taken from the deeper troughs.

The palaeontological evidence described in Appendices 3 and 4 suggests that the sediment reflects some of the climatic fluctuations following the last glaciation. Further work, including radiocarbon dating, is in progress.

The muds are not distributed evenly throughout the area, for example, over 150 m of sediment fills the entrance to Loch Linnhe but in the Sound of Mull and the Firth of Lorne observed sediment cover does not exceed 10 m. Commonly the muds form lenticular bodies deposited on the sides of slopes. Such a lenticle obscures the true configuration of the trough north-west of Coll and Tiree and its thickness contrasts with the thin cover lying in the deeps off Barra Island; another such deposit of sediment lies on the north side of the deep between Rhum and Skye.

Similar but more compact sediments have also been cored on the outer shelf where they lie beneath a thin cover of modern sands (Fig. 13).

### *Modern Sediments*

Coarse, shelly sands and gravels and soft, olive-grey, muddy sediments both lie on the

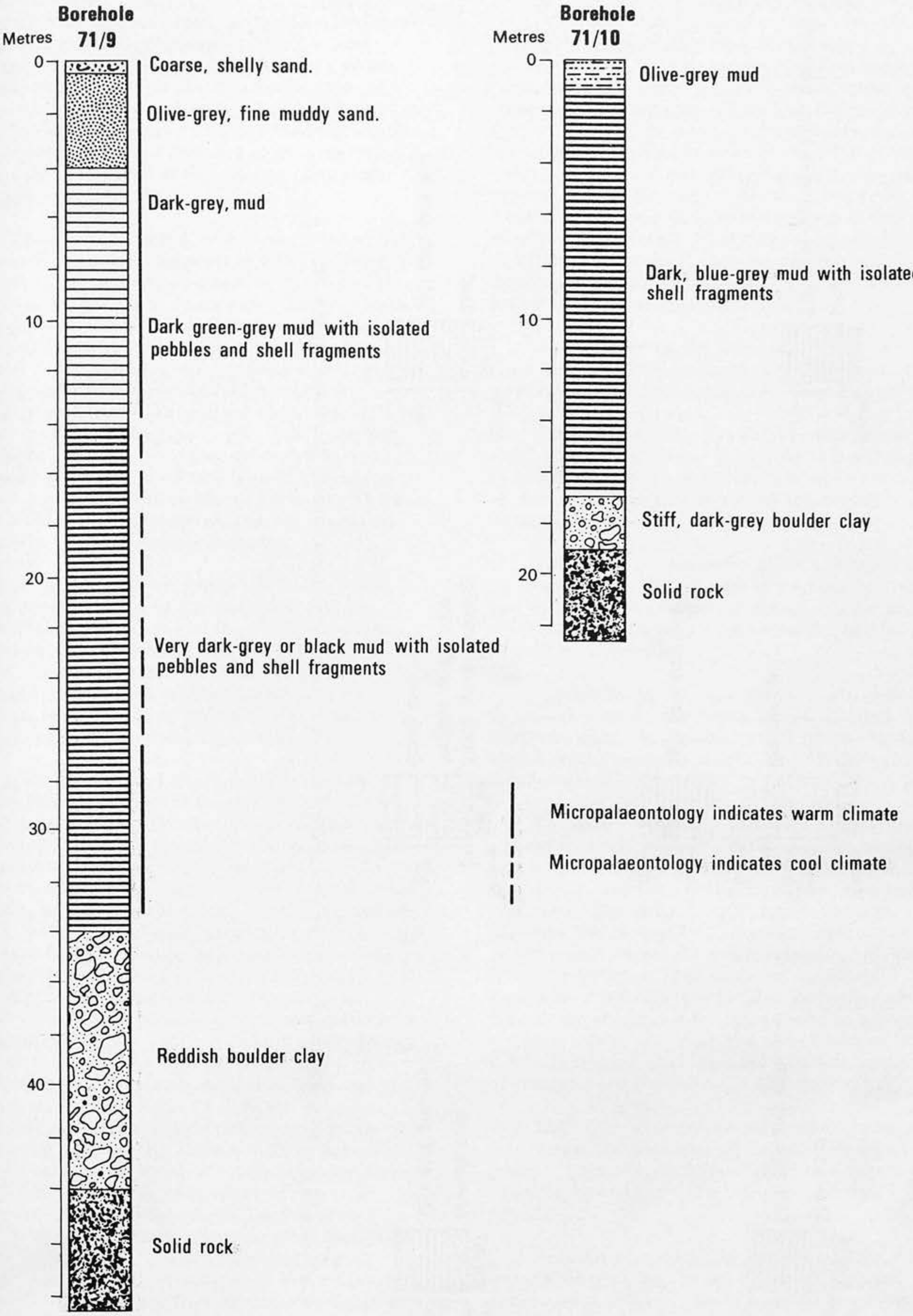


Fig. 12. Borehole sections 71/9 and 71/10. For location see Fig. 2

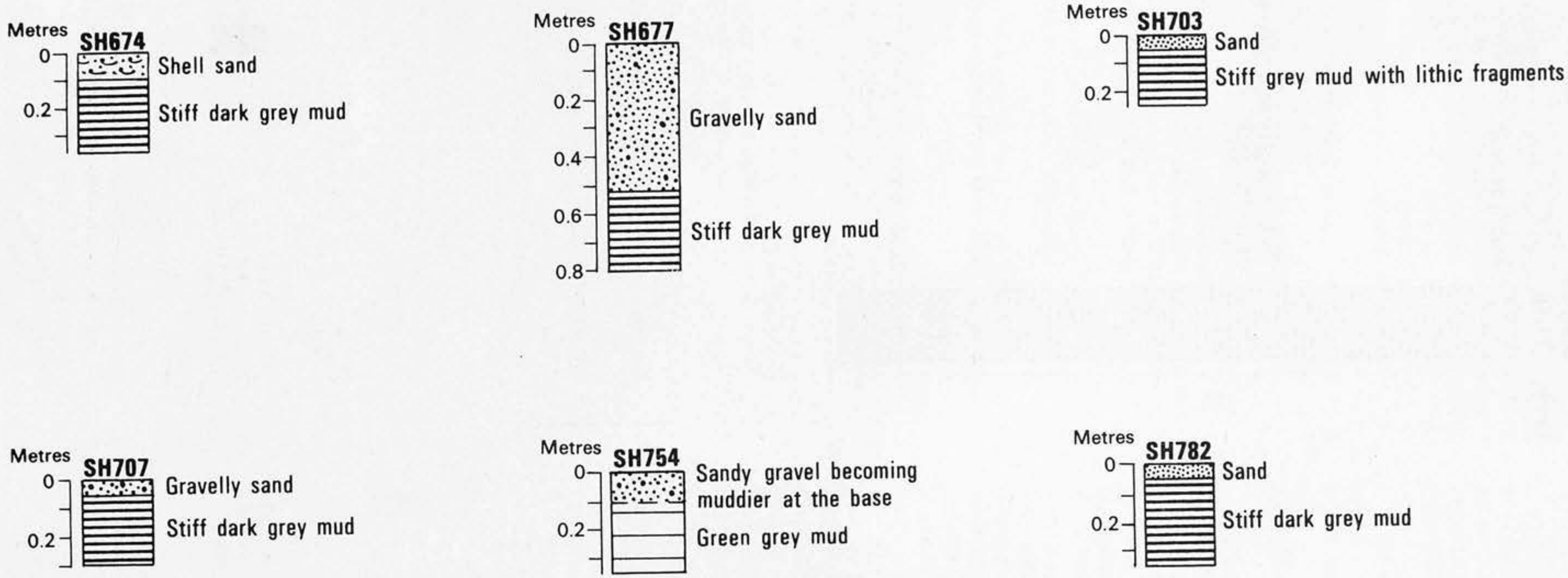


Fig. 13. Superficial sediment core sections, outer continental shelf. For location see Fig. 11

more compact late glacial and postglacial muds, and have been interpreted as modern sediment formed under the influence of the present marine regime possibly by reworking of the older sediment. On Stanton Banks, the Blackstones Bank and on the cobble spreads at the top of the continental slope modern sands have been observed forming ripples on relict, glacially deposited cobble floors (Eden and others, 1971; 1973).

The distribution of sea-floor outcrop and modern sediment is shown in Fig. 11. Rapid changes in lithology, reflecting strong relief, are not mappable by reconnaissance methods and it is possible to distinguish only the following five sea-floor types: muddy sediments, sands, sandy gravel and gravelly sand, gravels, and areas of predominant rock exposure. Muddy sediments include the divisions M, sM, mS, (g)M, (g)sM, (g)mS, gM, gmS, mG and msG on Fig. 11. Further subdivision is only locally possible as admixtures of gravel-grade shell and lithic debris derived from local rock or boulder clay exposures are not mappable with the present sample density.

Sediments of the group cover the main channel of the Sea of the Hebrides and the troughs and sea lochs of the Inner Hebrides. Inshore sampling by divers around Mull shows that, in areas sheltered from the south-westerly swell, fine grained sediments of the group extend to within 30 m of the shore where they grade rapidly into beach gravels.

The modal size of the sand fractions examined is estimated to lie within the fine and very fine sand grades. All samples contain varying amounts of shell debris (comminuted bivalve and echinoderm debris and foraminifera). The mineralogy is dominated by clear angular quartz with a low sphericity index; grains of very well rounded quartz, with medium to high sphericity index occur in many samples and some have traces of ferric oxide cement. Authigenic glauconite and pyrite fills the interiors of foraminiferal tests and glauconite also occurs free, either as casts of the tests or as ovoid pellets. Heavy mineral assemblages are being examined in detail and reported separately. To date the only significant concentration to be found is in Carsaig Bay, Mull. Here a 0.41 m core of fine, well sorted sand (SH 818) taken by divers was found by the Geochemical Division to contain approximately 3 per cent of free magnetite, but with much additional magnetite included in other, mainly ferromagnesian, minerals. The $TiO_2$ content of the magnetite was shown by X-ray fluorescence analysis to be about 10 per cent.

In the gravel fractions the relative proportions of lithic fragments and skeletal carbonate (mostly bivalve debris) vary considerably. *Turritella communis* Risso is common and in some samples constitutes the entire gravel fraction. Basalt is the main lithic type. Apart from those samples derived from the inshore sediments west of Skye the gravel is poorly sorted and has variable roundness and sphericity. It forms a separate mode from the finer part of the sediment with which it is admixed and its lack of sorting suggests that it is derived from local rock or boulder clay exposures (Eden and others, 1971) or by reworking of the glacial marine sediments.

Sands occur on the even sea floor between Colonsay and Stanton Banks and on the outer shelf west of Stanton Banks and the Outer Hebrides.

West of Colonsay the sand is fine to very fine, and well sorted. It retains this character over a large area. Its composition is similar to that of the sand fractions of the muddy sediments.

The sands on the outer shelf are coarser and have both a higher and more variable percentage of carbonate. Their mineral and lithic fractions, which vary considerably, are being examined in detail.

Sediments in the size range sandy gravels to gravelly sands are found in two distinct environments: in shallow water areas exposed to the south-westerly swell, and on the outer continental shelf.

The shallow water sediments are composed almost entirely of very coarse sand to pebble grade lithic and shell debris. The lithic fragments, mostly local rock types, are well rounded. The shell debris is abraded and includes the remains of bivalves, echinoderms, gastropods, serpulids and cirripedes. Samples from the Sound of Iona included substantial amounts of the calcareous alga *Lithothamnion*, fragments of which were also found in samples off Eigg island and from the west coast of Skye. A small amount of finer sand consists mainly of comminuted shell debris and quartz.

The sediments on the outer shelf lack the roundness and abrasion of the shallow water group. The composition of the lithic fractions is variable and they are being examined in detail.

Gravels occur locally amongst rock exposures such as the Skerryvore Bank and the shoals west of Iona. Most commonly, however, they form the beaches and small deltas on sheltered coasts backed by high ground. Sampling has indicated that they do not extend far offshore.

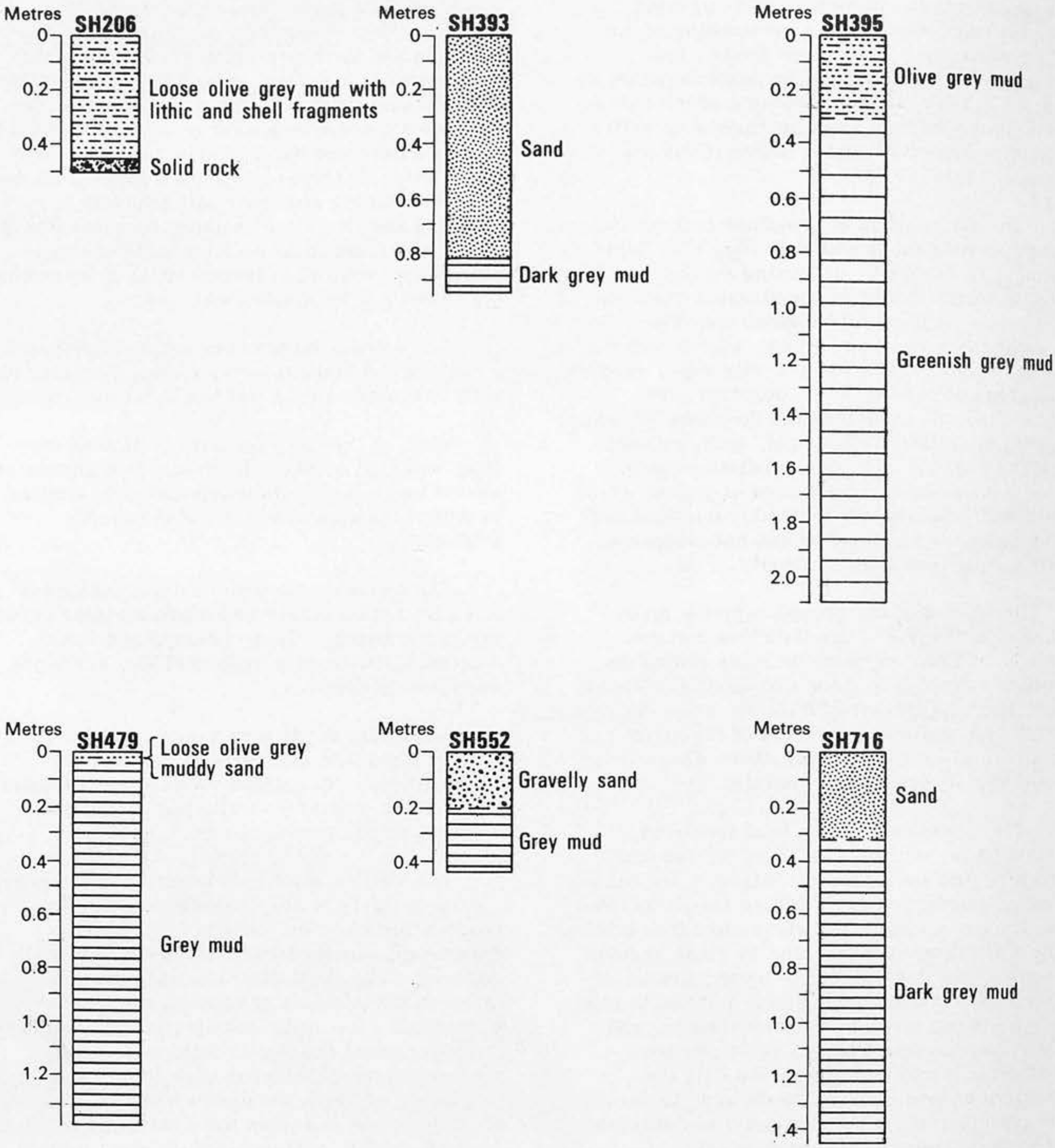


Fig. 14. Superficial sediment core sections, main channel of the Sea of the Hebrides. For location see Fig. 11

Areas such as Stanton Banks and the Blackstones Bank, which are areas of predominant rock exposure, have been described in detail by Eden and others (1971; 1973).

## Pre-Quaternary Geology: Discussion

The interpretation of solid geology (Fig. 2) is based primarily on the seismic, magnetic, gravity and sampling evidence outlined above. However, the coincidence of prominent features on the sea floor and structural and lithological changes deduced from geophysical evidence allows many boundaries to be interpolated from bathymetric evidence.

### *OUTLINE OF MAIN STRUCTURES AND FORMATIONS*

Evidence discussed in detail below suggests that the geology of the area is controlled by three major faults, the Minch Fault, the Camasunary-Skerryvore Fault and the Great Glen Fault. The first two mark the western margins of asymmetric troughs, floored by downfaulted Precambrian and Palaeozoic rocks, which rise south-eastwards to appear from beneath infilling Mesozoic sediments.

The Great Glen Fault, which on Mull does not significantly affect Mesozoic rocks, forms the northern margin of what is interpreted as a sedimentary basin in the marine area to the south.

There is evidence for a fourth fault-bounded trough west of the Outer Hebrides.

Tertiary igneous activity and north-west faulting have been superimposed on these structures. The faulting, which succeeded the igneous activity, in places raised the westward-tilting basement blocks and displaced their outcrop. It is suggested that such a movement, together with some north-eastward tilting of the downfaulted blocks may be responsible for the tapering of the Mesozoic outcrop in the south of the Sea of the Hebrides Trough. These large scale structures are similar to those observed on Atlantic-type continental margins. In particular the structure in this area resembles that of East Greenland, described by Haller (1970).

### *AREA WEST OF THE MINCH FAULT*

Rockhead is not seen on shallow seismic records west of 08° 30' W; it falls seawards and is overlain by a thickening sequence of Pleistocene sediments. This situation is similar to those described north-west of St Kilda (Stride and others, 1969) and west of Shetland (Watts, 1971). The western limit of outcropping rockhead, however, lies some 60 km from the continental slope in the present area compared with about 40 km at St Kilda and west of the Shetlands.

On magnetic, gravity and morphological evidence it is possible to make a tentative division of the rocks into a Lewisian group, a late Precambrian to Lower Palaeozoic group and a Mesozoic group.

Gravity evidence suggests that west of Barra Head a narrow, asymmetric trough of Mesozoic sediments, tilted to the east, lies on older rock. This is consistent with seismic and magnetic evidence, although no well developed bedding is seen on shallow seismic records. The north-west trends in rockhead topography suggest that Tertiary faulting, detected to the east of the Minch Fault, may continue into this area but there is no confirmatory evidence for this.

Off the east coasts of South Uist and Benbecula seismic evidence and samples (SH 206 and SH 207) show that Mesozoic rocks lie to the west of the Minch Fault which here is not defined by the steep gravity gradient present further south. The nature of the Lewisian-Mesozoic boundary is not certain; on Fig. 2 a scarp lying between 60 m and 120 m has been interpreted as the edge of the Lewisian. It is likely that the Mesozoic rocks here are analogous to the Lower Jurassic rocks resting on Torridonian sandstone to the west of the Camasunary Fault on Skye, and to the Trias resting on the Torridonian of Rhum.

### *MINCH FAULT TO THE CAMASUNARY-SKERRYVORE FAULT*

Between Skye and Benbecula the Minch Fault, which continues northwards into the Minch lies close to the Outer Hebrides and does not occupy the linear channel off Skye. The line of the fault (interpolated between deep reflection sections) is intersected by resistant Tertiary igneous rocks which are responsible for the irregular topography off South Uist and Benbecula. These have directed erosion to unintruded Mesozoic rocks beneath the linear channel.

Southwards the fault branches and can be traced to Barra Island on the deep reflection sections. Between two sections the faults pass through the area of the shoals off Pabbay Island. These shoals coincide with negative magnetic anomalies on both airborne and shipborne magnetometer records, and are interpreted here as Tertiary lavas. Further south the fault is seen on a deep reflection section (Fig. 8) where the Lewisian scarp is particularly pronounced; a third fault is also seen in this section, but both of the easterly faults have small throws compared with the major westerly

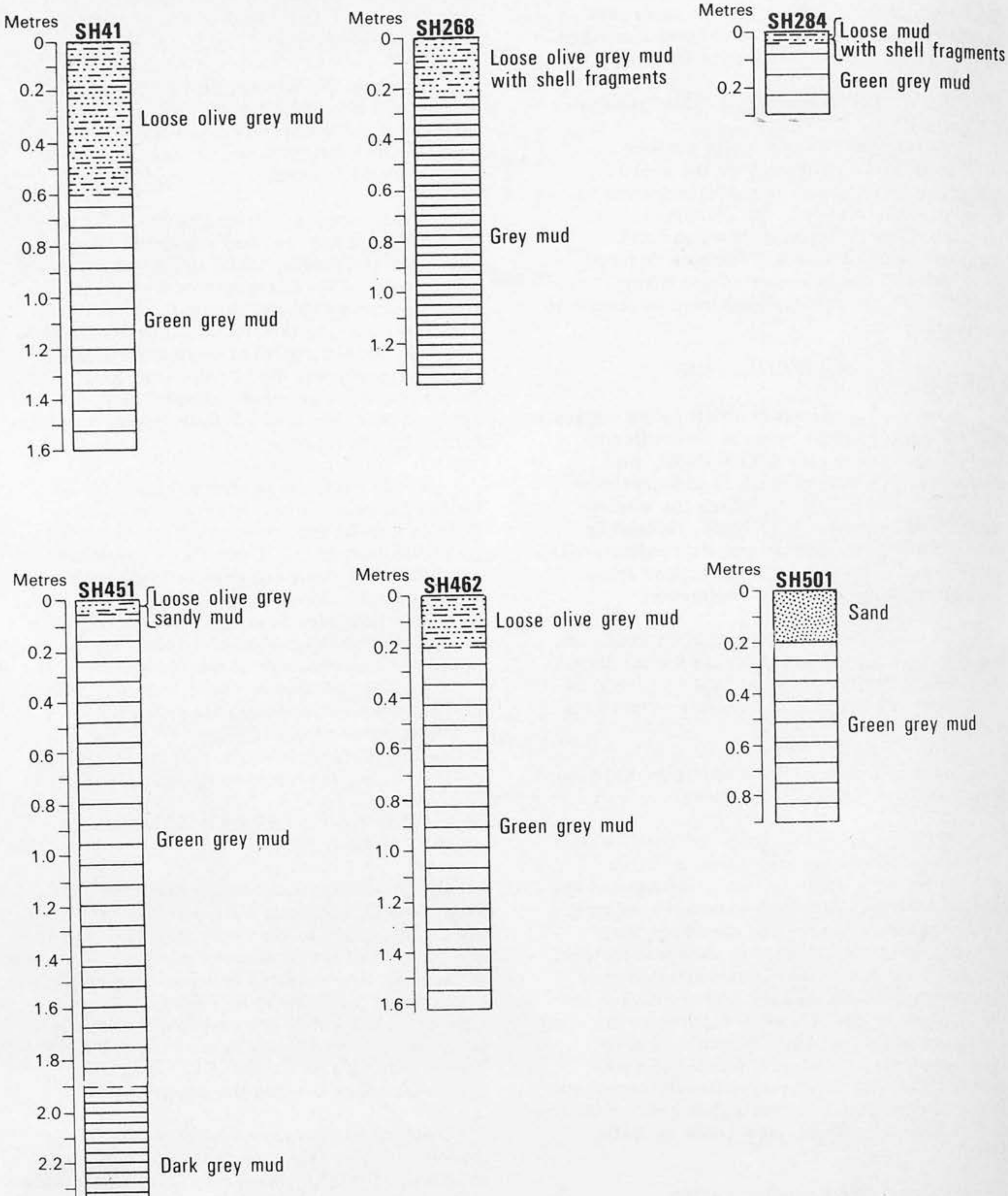


Fig. 15. Superficial sediment core sections, Inner Hebrides. For location see Fig. 11

branch. The westerly branch can be traced with confidence south-westwards until the scarp terminates. On topographic evidence, a southward extension of this branch is probable, and the fault may pass through a narrow depression in basement rocks where, although geophysical contrasts are low, there is some supporting shipborne magnetic evidence.

*Precambrian and Palaeozoic Geology*

Isochrons on the basal horizon B of the trough show that east of the Minch Fault this basement is uneven, with local structural depressions containing up to about 3 km of sedimentary rocks. In the north both seismic and gravity evidence suggest that these thick sediments continue under the lava flows of Skye and the Canna Ridge. Further south, off Coll and Tiree, horizon B rises steeply upwards to outcrop on Hawes Bank (Figs. 2 and 9) where samples of Torridonian sandstone (SH 767 and SH 768) have been collected. The strike of this slope, if continued northwards, coincides with the most westerly exposures of Torridonian sandstone on Rhum and south-west Skye. This extrapolation forms a trend parallel to gravity and magnetic features and is consistent with the presence of thick sediments under north-west Skye (Smythe and others, 1972).

South-west from Hawes Bank the basement-Mesozoic boundary takes on a more westerly trend, evident on seismic, magnetic and gravity records, until it intersects the Minch Fault to form a terminal wedge to the sedimentary trough. This structure is discussed below.

The exposure of seismic basement on Hawes Bank, together with the weak reflections beneath it on deep reflection profiles, suggest that it may be largely a Torridonian rock surface; the possibility that Lower Palaeozoic rocks are also present beneath this surface cannot, however, be discounted.

The boundary between the Torridonian of Hawes Bank and the Lewisian of Coll and Tiree is drawn on magnetic evidence (Fig. 4). South-west of Tiree the islet of Skerryvore is formed of a resistant Lewisian gneiss; sample SH 725 is a diopside-scapolite rock indicating that the exceptional anomalies on shipborne magnetometer traces across the area are caused by magnetite-rich bands in a variable gneiss, of which the diopside-scapolite rock forms a part. (Geological Survey one-inch sheets 42 and 50, Tiree). From the size of the area giving the exceptional anomalies it seems likely that less resistant, variable gneisses floor deeper areas of Skerryvore Bank (which also have lesser relief), whilst uneven shoals and rocks (as well as Skerryvore islet and Tiree itself) are formed of more resistant gneiss.

Stanton Banks, a group of rock shoals with variable gravity anomalies has also been interpreted on magnetic and sampling evidence as a Lewisian outcrop. Between the Skerryvore and Stanton Banks lies an area of resistant rocks associated with geophysical properties indicative of Torridonian rocks; weak magnetisation, high seismic velocity, and intermediate density. These rocks can be traced south-westwards from Hawes Bank, and for geological reasons are interpreted as comprising a downfaulted block of Torridonian.

Torridonian rocks extend east and south of Stanton Banks but the boundary with the Stanton Banks Lewisian does not appear to be faulted, leaving the possibility that the topographically lower Torridonian is lying in a pre-Torridonian depression in the Lewisian surface, a situation which commonly occurs in the North-west Highlands.

The possible presence of Old Red Sandstone and Carboniferous rocks within the trough is discussed in the section immediately below.

*Mesozoic Geology*

The younger rocks filling the Sea of the Hebrides trough reach a maximum thickness of about 2-3 km. Two gravity cores taken where these rocks outcrop (SH 133 p. 28 and SH 177 p. 29) contained Mesozoic rock, and shallow seismic profiles over the whole trough reveal a well bedded sequence which, off Neist Point, Skye, can be traced to the Middle Jurassic beds of this area. It is evident therefore that Mesozoic sediments constitute a significant proportion of the rocks in the trough.

Within the infilling rocks a dominant reflector, horizon A, has been noted and contoured in the deep reflection interpretation. This horizon does not outcrop in the north, and any attempt to estimate its age in this area must be tentative. The easterly-dipping Middle Jurassic beds of Neist Point can be traced westwards onto a deep reflection section, but the presence of dykes and the possibility of faulting allow the horizon to be dated here only as well below the Middle Jurassic.

Off South Uist horizon A is not present on a deep reflection section west of the Minch Fault. Samples of late Permian and probable Rhaetian age (SH 206 and SH 207) have been taken from this area indicating that the horizon is not older than this.

North-west of Coll and Tiree horizon A outcrops as a scarp, which forms the south-eastern margin of the glacial trench (Fig. 8) but it has not yet been sampled. Faulting also brings it to the surface in the centre of the sedimentary trough, where it outcrops as the Mesozoic shoal between Tiree and Barra Head. In this area A could represent a horizon or disconformity within the Mesozoic, the Mesozoic/Tertiary unconformity, or a Palaeozoic/Mesozoic unconformity; it is, however, unlikely to be the Mesozoic/Tertiary unconformity as this would require 1000 m of overlying Tertiary sediment, which is not consistent with the evidence of Mesozoic samples SH 133 and SH 177 or with the thin Tertiary succession on land.

That A represents a Palaeozoic (Old Red Sandstone or Carboniferous)/Mesozoic unconformity or a horizon in the lower Mesozoic is more probable. The 1000 m of sediment above A compares with thicknesses of Mesozoic on land (Richey and others, 1961, p. 20) and the remaining thickness between B and A in the trough would be consistent with the presence of Old Red Sandstone and/or Carboniferous sediments, the presence of the latter also being indicated by reworked Carboniferous miospores in SH 207. Mesozoic downwarping in the trough, however, might make this comparison invalid. If seismic correlations are correct an age near the boundary between the Permo-Trias and the Jurassic is the most probable but confirmation will be sought during a future drilling programme.

The age and nature of the Sea of the Hebrides Trough can be considered now. The western branch of the Minch Fault truncates Mesozoic rocks, indicating post-Mesozoic or syn-Mesozoic movement. The structure and stratigraphy of the trough is therefore analogous to that on southern Skye and Raasay where late Jurassic movement on the Camasunary-Skerryvore Fault throws down Mesozoic sediments against the Torridonian. The Sea of the Hebrides Trough is, however, much larger in scale.

The Minch Fault also resembles the Great Glen Fault in its scale and Caledonian trend, and Dearnley (1962, p. 158) has postulated Lower Palaeozoic wrench movement as an explanation for the distribution of structural zones in the Lewisian. The geological map shows that the fault zone follows a course close, but not identical, to that suggested by Dearnley and earlier workers. In particular it lacks the rectilinear character which could be cited as evidence for its transcurrent nature, and throughout much of its length follows a line a few kilometres to the east of the low angle Outer Isles Thrust, which is possibly the earliest line of structural weakness along which subsequent dislocations have developed.

It is most probable therefore that the Minch Fault has had a complex history, initiated as a Caledonian structure, possibly re-activated by Hercynian stresses to give transcurrent displacement (though the present work provides no evidence of this) and finally reacting to Mesozoic and early Tertiary tension with large vertical movements. The non-rectilinear nature of the fault, as it appears on the present surface, may be caused by differential amounts of dip along the line of the fault during vertical movement and does not necessarily exclude the possibility of a phase of transcurrent movement. A remaining problem is the structural significance of the fault mapped geophysically between Idrigill Point on Skye, southwards to where it joins the Minch Fault zone 10 km east of Barra; present evidence indicates that this fault is a splay from the Minch Fault.

In their Palaeozoic and Mesozoic history the Minch Fault and the Sea of the Hebrides Trough, together with the Camasunary-Skerryvore Fault and the Inner Hebrides Trough, are broadly similar in structure and stratigraphy to the rocks of East Greenland, described by Haller (1970).

*Tertiary Geology*

Tertiary faulting and igneous activity are a major controlling factor of the surface geology. Within the area of the trough, two Tertiary centres occur, both close to the Camasunary-Skerryvore Fault. Present work shows a large extension of the north Skye basalt flows south-westwards to form the Canna Ridge, though as has been shown, thick Mesozoic sediments probably underlie this ridge. Magnetic evidence suggests that the shoal to the south-west of the Canna Ridge and the shoals off Pabbay Island are also capped by lavas. Off northern Skye, dolerite sills are detected on shallow seismic and magnetic records and outcrop as a series of shoal areas rising to 80 m below sea level.

Close to the line of the Minch Fault zone, a series of shoals have been identified as igneous rock from the evidence of shallow seismic and shipborne and airborne magnetic records. The geophysical character is similar to that associated with the Canna Ridge and it seems probable that these shoals are either outliers of Tertiary basalt lava or Tertiary sills.

The observed relationship between the Minch Fault zone and Tertiary igneous rocks near Pabbay strongly suggests that the western branch of the fault system has also experienced vertical movement postdating the Tertiary lavas, this situation being analogous to that seen on Raasay.

The transgression of basement outcrop across the southern part of the trough has been mentioned above. The size of the vertical movement involved to bring the basement to the surface excludes the possibility that this is an effect of basement relief. Similar movement of basement outcrop by north-west trending Tertiary faulting occurs on a range of scales on land and we suggest that such faulting is in part responsible for the outcrop distribution in the Sea of the Hebrides Trough. Such faulting would not greatly displace the outcrop of the steeply hading Minch Fault but would significantly affect the outcrop of gently dipping basement. Southwards to Tiree the narrowing of the trough in part reflects the converging trends of the Minch and Camasunary-Skerryvore faults but the differential narrowing of the Mesozoic area requires explanation. Tilting of the basement about a north-west axis through north Skye could account in part for this narrowing but in the extreme south north-west trending faults have been detected which account more plausibly for the much stronger transgression of basement outcrop in this area.

An east-west Tertiary trend, possibly fault controlled, is defined by the rectilinear northern margin of Hawes Bank and the Tertiary lava shoal to the west.

### *CAMASUNARY-SKERRYVORE FAULT TO GREAT GLEN FAULT*

The Camasunary Fault can be traced southwards from Skye. The presence of the fault in Fig. 10 is evident from the contrast between the even, bedded surface to the east, proved to be a Mesozoic sandstone (Borehole 71/10), and the uneven Torridonian surface to the west. South of Rhum it is visible on a shallow seismic section showing bedded sediments, which occupy the floor of the trench between Rhum and Eigg, faulted against the Rhum Torridonian; the latter forming the western wall of the trench. Southwards again the cover of lavas prevent detection of the fault on shallow seismic records, and interference from the Ardnamurchan plutonic centre obscures the gravity evidence.

Offshore, east of Coll, a strong gravity gradient indicates the presence of a fault close to the coast, probably following the deep submarine trench, and here interpreted as the southward extension of the Camasunary Fault on the basis of its structural similarity and referred to as the 'Camasunary-Skerryvore Fault'. It is assumed to throw Mesozoic rocks, in places covered by lavas, down to the east against the Lewisian of Coll and Tiree.

Off the Skerryvore Bank the fault is clearly seen on shallow and deep seismic sections and forms a prominent Lewisian scarp similar to the Minch Fault scarp south of the Outer Hebrides.

South-east of Stanton Banks bedded sediments are seen on shallow seismic records. They abut against Torridonian or Palaeozoic rocks and the fault, which is evident on gravity and aeromagnetic maps, occupies the base of the trench off Stanton Banks.

The asymmetrical nature of this trough, here referred to as the Inner Hebrides Trough, is evident on southern Skye where some 13 km east of the Camasunary-Skerryvore Fault, Triassic and Liassic rocks rest unconformably on the Torridonian. East of Eigg, bedded sediments on shallow seismic records have been interpreted as Mesozoic; the boundary between these and the Moine of Morar is not clear, but is probably an unconformity similar to that to the north, on Skye, and to the south, on Ardnamurchan.

Further south the asymmetrical nature of the trough is again evident on shallow and deep seismic sections crossing the Skerryvore Bank. A basal horizon is thrown some 2 km down at the fault and rises to the surface 7 km to the south-east as the rockhead high. Geophysical evidence of structural similarity to the Inner Hebrides Trough on Skye indicates that Mesozoic rocks fill the trough here also. In the north it is clear that Torridonian or metamorphosed Lower Palaeozoic rocks form the floor of the trough. In the south the rockhead high opposite the Skerryvore Bank has not been sampled and the presence of intrusions in the region of the Blackstones Plutonic Centre (which lies in an analogous situation to the Ardnamurchan centre) obscures the surrounding geology. Aeromagnetic evidence however indicates that the shoals west of Iona are formed of Precambrian or Lower Palaeozoic rocks.

The broad picture is then of an asymmetric, faulted trough extending from Skye and Raasay, southwards past the Blackstones Bank. It is floored by Lower Palaeozoic rocks and filled with a wedge of Mesozoic rocks of variable thickness and width. Its origin is evident on Skye where the main period of movement on the fault has been dated as late Jurassic to early Tertiary (Peach and others, 1910).

As in the Sea of the Hebrides Trough Tertiary faulting and igneous activity are important. The Tertiary plutonic centres of Skye, Rhum, Ardnamurchan and the Blackstones Bank lie close to the Camasunary-Skerryvore Fault and similarly the Mull centre is close to the Great Glen Fault.

Magnetic and morphological evidence has

been used to define the boundary of the lavas which extend southward from Muck to north-west Mull, outcropping and forming a rugged sea floor in this area.

The lava scarp south of Staffa and Ulva islands may be fault controlled, as the lava base on the Ardmeanach Peninsula rests on Cretaceous sediments some 150 m above sea level. Southward, observed Tertiary faulting on this peninsula again drops the lava base to below sea level, to be raised again on the Ross of Mull by the Loch Assapol Fault, which lifts it above the present level of erosion and exposes Moine schists. The fault has been extended northwards along a steep scarp in rockhead but cannot be traced further on geophysical evidence. It may continue west-north-west throwing the lavas and underlying Mesozoic down, first against the Torridonian or Lower Palaeozoic rocks, which form the shoals west of Iona, and then against the Mesozoic which rests on them in the Inner Hebrides Trough. The aeromagnetic map shows that the lavas to the east of the fault do not continue southwards under the sea and the fault cannot be traced here.

North of the Blackstones Bank a triangular area of resistant rock with moderate amplitude magnetic anomalies has been interpreted as a faulted block of Lewisian lying between Mesozoic rocks. Whilst the easterly fault is clear on the deep reflection profile and is marked by a scarp on rockhead, the south-westerly fault is tentative. The easterly fault may continue over the Blackstones Bank and be responsible for the depression running across it.

The relationship between the Camasunary-Skerryvore Fault and the lavas east of Coll is similar to that seen on Raasay and suggests post lava movement on the fault in this area.

*GREAT GLEN FAULT AND AREA TO THE SOUTH-EAST*

The geology of this area has not been studied in detail. The Great Glen Fault (Kennedy, 1946) has been previously traced to Loch Buie on the south coast of Mull (Lee and Bailey, 1925, p. 5). South of Loch Buie the fault is marked by a linear anomaly on the aeromagnetic map. This line coincides with a series of shoals shown on detailed Admiralty surveys to have a rectilinear southern margin. The shoals are interpreted as the southern continuation of the igneous and metamorphic rocks of south-west Mull and Iona and their southern margin as the Great Glen Fault scarp.

South of the fault, rockhead plunges beneath a thick layer of Quaternary sediments, generally beyond detection on the shallow seismic records, until it reappears again as the Torridonian of Colonsay. East of Colonsay, drilling by the Institute has proved a red sandstone (Borehole 71/9) and a sedimentary basin probably extends north of Colonsay to the fault. Further, the high degree of differential erosion between Tertiary intrusions and country rock, evident east of Colonsay, is again present to the north-west. This suggests the presence of sedimentary rocks flooring the depression in rockhead west of Colonsay. Our most southerly detected position of the fault is on a deep reflection profile, south-east of the Blackstones Bank, where the fault line is seen to be swinging towards a more westerly trend.

The presence of red sandstone close to the east coast of Colonsay, together with the linear channel off the south-east coast, indicates that the coastline is fault controlled, but no complementary fault off the west coast of Jura has been detected. A marked change in the bathymetry occurs at the entrance to the Firth of Lorne, however, and has been interpreted as an unconformity of sandstone on Dalradian metamorphic rocks. To the east, deep north-east trending channels are characteristic of the glaciated Dalradian; to the west a thick drift sequence, lying on less resistant rocks, gives rise to lower relief. This interpretation is consistent with the aeromagnetic evidence.

## Quaternary Geology: Discussion

*GLACIATION*

No sediments predating the last glaciation have yet been cored and the only new evidence relating to glaciation is the morphology of rockhead (Fig. 2), which, on the inner shelf, has been interpreted as a glaciated surface throughout the area.

The movement of the ice sheet during maximum glaciation has been deduced from glacial striae and erratic boulders on land as being from east to west. This contrasts with the north-east or north-north-east trend of many erosional features in the marine area. The most striking of these features is the trench running south-westwards from Canna and Rhum. It appears that at some stage during glaciation ice from the mountains of Rhum, together with ice from Skye travelling through the channel between Rhum and Canna, excavated or enlarged this trench. Additional ice was contributed by the tributary trench north of Hawes Bank.

Ice from western Skye also excavated or enlarged a south-westerly trending trench north-west of the Canna Ridge and an overdeepened re-entrant into the ridge with a similar trend lies west-south-west of Canna. On the opposite side of the main channel, tributary troughs, originating on the Outer Hebrides, curve south-westwards to parallel the main trend.

The combined evidence from land and marine areas suggests that the south-westerly features were formed during growth of the ice cover or during earlier glaciations, presumably following inherited, structurally controlled depressions. Subsequently mainland ice invaded the area from the east, leaving striae and erratics on the higher ground which is now land.

### *LATE GLACIAL AND POSTGLACIAL SEDIMENTATION*

Until palaeontological examination of core and borehole material is completed and correlated with geophysical evidence and radiocarbon dates only tentative conclusions can be drawn.

The palaeontological changes described in Appendices 3 and 4, however, probably reflect the climatic ameliorations of pollen zone II followed by the deterioration of zone III and the final amelioration in zone IV.

During deglaciation a large amount of boulder clay would have been available for winnowing by the sea and this together with finer fluvioglacial material probably accounts for the thickness of late glacial and postglacial muds.

Truncation of horizons within the Quaternary sediment sequence west of Barra Head suggests that erosion of the sediments by a postglacial marine regime may have occurred.

### *DISTRIBUTION OF SEDIMENTS ON THE MODERN SEA FLOOR*

The high percentage of carbonate together with the thickness of modern sediment show that deposition is at present slow. Most of the unconsolidated material available on land following glaciation was probably quickly transported and deposited leaving resistant glaciated surfaces of crystalline rock.

Grain size distribution (Fig. 11) is related primarily to bathymetry but situation with respect to the prevailing south-westerly swell and to tidal currents is also an important control. Laboratory work in progress suggests that carbonate content is highest close to sea-floor outcrop; south-westerly facing beaches close to areas of sea-floor outcrop are composed almost entirely of shell sand.

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## Appendix 1: Mesozoic Microfossil Assemblages by G. Warrington

*Sample Station SH 133 (CSA 29)*

Miospores:

? Harrisispora equiexina (Couper) Pocock 1970

? Leptolepidites cf. major Couper 1958

Osmundacidites wellmanii Couper 1953

O. cf. wellmanii

O. sp.

Lycopodiumsporites cf. clavatoides Couper 1958

Tsugaepollenites mesozoicus Couper 1958

Abietineaepollenites cf. dunrobinensis Couper 1958

A. sp.

Alisporites thomasii (Couper) Nilsson 1958

Microcachryidites sp.

Perinopollenites elatoides Couper 1958

Cycadopites minimus (Cookson) Pocock 1970

Classopollis torosus (Reissinger) Balme 1957

Bisaccate spp. indet.

Organic-walled microplankton:

Crassosphaera concinna Cookson & Manum 1960

The standard of preservation of this assemblage is generally poor, particularly in the case of many of the bisaccate miospores. Specimens are, however, fairly abundant. The majority of the taxa recorded have been noted in both the Jurassic and Lower Cretaceous; exceptions include Leptolepidites major (Middle Jurassic, Couper 1958; Toarcian to Bathonian, Tralau 1968), Abietineaepollenites dunrobinensis (Lower Lias, Couper 1958), Alisporites thomasii (Jurassic, Couper 1958; Lower and Middle Jurassic, Nilsson 1958) and Crassosphaera concinna (Cretaceous and Tertiary, Cookson & Manum 1960). However, the range of the latter species is not precisely defined and it may well extend below the Cretaceous; this would explain its apparent anomalous occurrence with Jurassic miospores. Other representatives of the genus have been recorded from the Toarcian (Wall, 1965). The composition of the assemblage is such, however, that it is impossible to date the sample more precisely than Jurassic to early Cretaceous.

*Sample Station SH 166 (CSA 30)*

Miospores:

Lycopodiumsporites clavatoides Couper 1958

? Abietineaepollenites sp.

Alisporites thomasii (Couper) Nilsson 1958

Brachysaccus microsaccus (Couper) Mädler 1964

Ovalipollis ovalis Krutzsch 1955

Vitreisporites cf. subtilis (de Jersey) de Jersey 1962

Perinopollenites elatoides Couper 1958

Bisaccate spp. indet.

The standard of preservation of this assemblage was fairly good although only about 100 specimens were obtained from the sample. The association of Ovalipollis ovalis, a miospore which ranges from the late Triassic into the Callovian (Schulz and Mai, 1966), with Lycopodiumsporites clavatoides and Perinopollenites elatoides indicates a Liassic to early late Jurassic age for the sample. The remaining taxa support this age determination; Alisporites thomasii was, as Pteruchipollenites thomasii, assigned a Jurassic range by Couper (1958) but Nilsson (1958) restricted the range of the form to the Lower and Middle Jurassic. The form Brachysaccus microsaccus is recorded as ranging from the Middle Rhaetic to the Upper Jurassic (Schulz 1967).

*Sample Station SH 206 (CSA 34)*

Miospores:

Anapiculatisporites spiniger (Leschik) Reinhardt 1962

? Osmundacidites sp.

Heliosporites altmarkensis Schulz 1962

Alisporites cf. thomasii (Couper) Nilsson 1958

Corollina meyeriana (Klaus) Venkatachala & Góczán 1964

Classopollis torosus (Reissinger) Balme 1957

Bisaccate spp. indet. and sporites spp. indet.

Calcareous microplankton:

Organic test-linings of foraminifera

The above assemblage is indicative of a late Rhaetian or early Liassic age. The former age is favoured because Corollina meyeriana and Anapiculatisporites spiniger have documented ranges extending from the Carnian into the Rhaetian and are only questionably known from the

Hettangian in the case of C. meyeriana and as occasional specimens in the case of A. spiniger (Schulz 1967). Heliosporites altmarkensis ranges from the late Rhaetian into the Hettangian. The overlap of the ranges of these three miospores occurs, therefore, in the late Rhaetian or possibly the earliest Hettangian.

*Sample Station SH 207 (CSA 33)*

Miospores:

Densosporites sp.

Lueckisporites virkkiae (Potonié & Klaus) Clarke 1965

? Taeniaesporites sp.

Protohaploxypinus jacobii (Jansonius) Hart 1964

cf. Jugasporites delasaucei (Potonié & Klaus) Leschik 1956

J. lueckoides Klaus 1963

J. sp.

Labiisporites granulatus Leschik 1956

Klausipollenites schaubergeri (Potonié & Klaus) Jansonius 1962

Falcisporites zapfei (Potonié & Klaus) Leschik 1956

Alisporites sp.

Bisaccate spp. indet. and sporites spp. indet.

With the exception of the specimens of Densosporites (which displayed a different mode of preservation to the remaining specimens in the assemblage and which are considered to be derived and of Carboniferous age) the miospores in the above assemblage are of Zechstein (late Permian) age.

*Borehole 71/10 (CSA 555)*

Miospores:

? Conbaculatisporites sp.

Lycopodiumsporites clavatoides ? Couper 1958

Tsugaepollenities mesozoicus Couper 1958

Alisporites thomasii (Couper) Nilsson 1958

Perinopollenites elatoides Couper 1958

Classopollis torosus (Reissinger) Balme 1957

Bisaccate spp. indet. and sporites spp. indet.

Organic-walled microplankton:

Baltisphaeridium sp. (sensu Downie & Sarjeant 1963)

Micrhystridium sp. (sensu Downie & Sarjeant 1963)

The taxa recognised in the above assemblage permit only a dating of Jurassic or possibly early Cretaceous age.

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## Appendix 2: Mesozoic Macrofossils from Borehole 71/10 by H. C. Ivimey-Cook

Seven samples were received from between 19.31 m and 20.56 m. The following taxa were identified:

Tetrarhynchia?

Gryphaea?

Meleagrinella? or Oxytoma?

Modiolus sp. [juv.]

belemnite indet.

fish fragments

The fragmentary macrofossils obtained are not sufficient for a certain identification of age but when combined with consideration of the lithology strongly suggest comparison with the Scalpa Sandstone, with an age of high Lower Pliensbachian to Upper Pliensbachian (top Lower to Middle Lias).

## Appendix 3: Quaternary Organic-Walled Microplankton from Boreholes 71/9 and 71/10 by R. Harland

*Borehole 71/9*

Eight samples from Borehole 71/9 (Figs. 11 and 12) were submitted for palynological analysis from the following depths beneath the sea floor: 1.5 m, 2.8 m, 6.0 m, 10.0 m, 16.0 m, 20.0 m, 26.0 m and 30.0 m.

All the samples yielded organic-walled microplankton but the samples at 16.0 m, 20.0 m and 26.0 m were poorer in their yield than the other samples. This less productive sequence together with differences in the assemblages of the microplankton enabled the borehole to be divided into three portions.

The uppermost part of the borehole, down to 10 m, yielded good assemblages of the microplankton. These assemblages were all dominated by species of Spiniferites and Peridinium with slight variations in the proportions of other species. A composite list of the species, given in their order of abundance, is tabulated below; both the palaeontological and neontological names are given where applicable (see Wall and Dale, 1968).

| | % | % | % |
|---|---|---|---|
| Spiniferites membranaceus (Rossignol) Sarjeant 1970<br>Spiniferites cf. pachydermus (Rossignol) Sarjeant 1970<br>Spiniferites cf. ramosus (Ehrenberg) Sarjeant 1970<br>= Gonyaulax spinifera (Claparède & Lachmann) Diesing 1866<br>Spiniferites sp. nov.<br>Spiniferites sp. | 29.4 | (47.15) | 70.6 |
| Peridinium cf. conicoides Paulsen 1905<br>Peridinium cf. leonis Pavillard 1916<br>Peridinium cf. oblongum (Aurivillius) Paulsen 1907<br>Peridinium cf. pentagonum Gran 1902<br>Peridinium sp. | 18.2 | (38.5) | 58.8 |
| Baltisphaeridium sp. | 6.3 | (14.85) | 33.3 |
| Operculodinium centrocarpum (Deflandre & Cookson) Wall 1967<br>= Protoceratium reticulatum (Claparède & Lachmann) Bütschli 1885 | 3.9 | (8.2) | 17.3 |
| Gen. et sp. nov. | 0.0 | ( - ) | 12.5 |

The percentages quoted give the minimum, arithmetic mean and maximum of the microplankton using all available samples.

This assemblage is essentially modern in aspect and indicates environmental conditions similar to those existing today.

The samples at 16.0 m, 20.0 m and 26.0 m indicate a different environment detrimental to the microplankton. This may be climatic in origin and be reflected in changes in temperature and salinity of the watermass.

The lowermost sample at 30.0 m contained a very rich assemblage of microplankton. Important changes in the proportions of the various species were noted in this assemblage indicating that environmental conditions at the time of deposition were different both from modern times and from those represented by samples at 16.0 m, 20.0 m and 26.0 m.

The assemblage is given below:

| | % |
|---|---|
| Peridinium cf. leonis Pavillard 1916<br>Peridinium sp. nov.<br>Peridinium sp. | 54.2 |
| Operculodinium centrocarpum (Deflandre & Cookson) Wall 1967<br>= Protoceratium reticulatum (Claparède & Lachmann) Bütschli 1885 | 28.8 |
| Spiniferites cf. ramosus (Ehrenberg) Sarjeant 1970<br>Spiniferites sp. | 13.6 |
| Gymnodinialean? cyst cf. Gyrodinium sp. (see pl. 4, fig. 29 of Wall & Dale 1968) | 1.7 |
| Baltisphaeridium sp. | 1.7 |

This assemblage dominated by Peridinium spp. differs from those described above in having a higher proportion of Operculodinium centrocarpum, a cyst which seems to be an indicator of the Gulf Stream/North Atlantic Drift water mass (Williams, 1971), and a lower proportion of the Spiniferites spp. This assemblage appears to correspond very closely with that described as the Peridinium spp. assemblage from the Firth of Clyde (Deegan and others, 1973) and may be contemporaneous.

*Borehole 71/10*

Seven samples from Borehole 71/10 (Figs. 11 and 12) were submitted for palynological analysis from the following depths beneath the sea floor: 0.05 m, 0.10 m, 0.5 m, 1.0 m, 2.6 m, 10.00 m, and 14.0 m.

All samples yielded organic-walled microplankton which have enabled the sequence in this borehole to be subdivided into upper, middle and lower parts. The uppermost part of the borehole down to 0.10m contains the following microplankton.

| | % | % | % |
|---|---|---|---|
| Spiniferites mirabilis (Rossignol) Sarjeant 1970<br>= Gonyaulax spinifera (Claparède & Lachmann) Diesing 1866<br>Spiniferites cf. membranaceus (Rossignol) Sarjeant 1970<br>Spiniferites cf. multiplicatus (Rossignol) Sarjeant 1970<br>Spiniferites cf. pachydermus (Rossignol) Sarjeant 1970<br>Spiniferites sp. nov. A<br>Spiniferites sp. nov. B<br>Spiniferites sp. | 35.6 | (44.0) | 52.4 |
| Operculodinium centrocarpum (Deflandre & Cookson) Wall 1967<br>= Protoceratium reticulatum (Claparède & Lachmann) Bütschli 1885 | 21.4 | (26.7) | 31.1 |
| Peridinium cf. pentagonum Gran 1902 | 11.0 | (12.6) | 11.0 |
| Baltisphaeridium sp. | 7.1 | (12.4) | 17.8 |
| Gen. et sp. nov. | 0.0 | ( - ) | 4.5 |
| ?Leptodinium sp. | 0.0 | ( - ) | 4.5 |

This assemblage, which is dominated by species of the genus Spiniferites, is comparable with that described in the uppermost part of 71/9. It differs, however, in having a lower percentage of Peridinium spp. and a higher percentage of Operculodinium centrocarpum. This may be due to a slight difference in watermass parameters because of variations in the extent to which oceanic waters have invaded the Sea of the Hebrides.

Samples 0.5 m, 1.0 m and 2.6 m yield very poor microplankton assemblages and are not considered any further. They are, however, comparable to the zone of poor productivity in borehole 71/9.

The lowermost samples, at 10.0 m and 14.0 m are rich in microplankton and contain an assemblage which differs from that described above. Species present are given below.

| | % | % | % |
|---|---|---|---|
| Peridinium cf. conicoides Paulsen 1905<br>Peridinium cf. denticulatum Gran & Braarud 1935<br>Peridinium cf. leonis Pavillard 1916<br>Peridinium sp. | 38.8 | (41.85) | 44.9 |
| Gen. et sp. nov. | 27.8 | (31.15) | 34.5 |
| Operculodinium centrocarpum (Deflandre & Cookson) Wall 1967<br>= Protoceratium reticulatum (Claparède & Lachmann) Bütschli 1885 | 0.0 | ( - ) | 24.2 |
| Baltisphaeridium sp. | 20.7 | (21.45) | 22.2 |
| Spiniferites sp. | 5.55 | ( 7.95) | 10.35 |
| Gymnodinialean? cyst | 0.0 | ( - ) | 5.55 |

This assemblage is dominated by cyst species of the dinoflagellate genus Peridinium and it is similar to both the lowermost assemblage of borehole 71/9 and to the Peridinium spp. assemblage of the Firth of Clyde boreholes. It differs slighly in having a high proportion of Gen. et sp. nov; the reason for this is not known and there is very little data available on this cyst. The presence of Operculodinium centrocarpum in substantial numbers is a good indicator of the influence of the North Atlantic Drift.

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## Appendix 4: Quaternary Foraminifera from Boreholes 71/9 and 71/10

by M. J. Hughes

*Borehole 71/9*

Eleven samples of Borehole 71/9 (Figs. 11 and 12) were submitted for examination from the following depths beneath the sea floor; 1.5 m, 2.8 m, 6.0 m, 10.0 m, 14 m, 16.0 m, 20.0 m, 24 m, 26.0 m, 28 m and 30.0 m.

The species of foraminifera are predominantly benthonic and three assemblages have been identified. The earliest is represented by samples from 30 m and 28 m dominated by Ammonia cf. batavus (Hofker), suggesting a warm interval with a water depth no greater than at present.

The second assemblage which commences at 26 m and continues up to 16 m is dominated by Elphidium clavatum (Cushman), with large Miliolidae as an important group in the coarser fractions. The numbers of species are low.

The third assemblage, which commences at 14 m, gradually changes its composition as it becomes younger in age. E. clavatum declines in importance whilst the Miliolidae continue to dominate the coarser fractions of the lower samples. However as the assemblage becomes younger large thick-shelled forms such as Rosalina globularis d'Orbigny, Cibicides lobatulus (Walker & Jacob), Planorbulina mediterranensis d'Orbigny and the arenaceous species Textularia sagittula Defrance, become important factors in the coarse fractions in addtion to the Miliolidae. In all the samples the number of foraminifera as well as the number of species represented is high in all size fractions.

The sequence is marine throughout with continuous connections with the open ocean demonstrated by the small, but persistent, presence of planktonic forms. The number of foraminiferal species does not fall very low or the total number of a single species rise very high in any of the assemblages so extreme ecological conditions are not encountered.

The presence of A. batavus as the dominant form in the lowest assemblage indicates a palaeoclimate similar to that of the present; this species reappears in the highest samples as a minor component. Palaeoecologically, where E. clavatum is a dominant species it is usually indicative of cold water conditions. This assignment of the middle assemblage to a cool period is also substantiated by the record of Q. agglutinata and several other cold water forms. The highest assemblages, in which the cold water forms decrease progressively upwards, indicate a gradually ameliorating climate. Two hundred specimens per gram of sand residue recovered from the sea-floor sample suggest that the present environment is actively depositing sediment in contrast to the conditions represented at the top of Borehole 71/10.

*Borehole 71/10*

Seven samples from Borehole 71/10 (Figs. 11 and 12) were submitted for examination from the following depths beneath the sea floor: 0.05 m, 0.10 m, 0.5 m, 1.0 m, 2.6 m, 10.0 m and 14.0 m.

The number of species of foraminifera is consistent throughout the sequence and though less diverse than that of borehole 71/9 the microfauna is not so restricted as to indicate an extreme ecological condition.

The percentage of each species in relation to the total population varies in such a way that a three-fold division of the sequence is apparent. Throughout the section examined the fauna is dominated by Elphidium spp. The samples at 14 m and 10 m contains, in addition, Bulimina marginata d'Orbigny, Hyalinea balthica (Schroeter), Cassidulina crassa and Ammonia sp., indicating water deeper than that inferred for the area of Borehole 71/9. The sample at 2.6 m is differentiated by the absence of H. baltica and a reduction in the numbers of Ammonia sp. and a marked increase in the percentage of C. crassa suggesting a slight shallowing of the water depth. The samples above this level, at 1.0 m, 0.5 m, 0.1 m and 0.05 m, are distinguished by the reappearance of H. baltica and a substantial increase in the numbers of B. marginata and a reduction in the percentage of C. crassa, again suggesting a return to deeper water conditions. The number of specimens per gram of sand residue from the sea-floor sample is over 20 000, which is interpreted as indicating a non-depositional environment.

*Conclusions*

It is impossible to correlate the microfaunas from boreholes 71/9 and 71/10 as the foraminiferal elements are so dissimilar. However, both sequences represent conditions where there appears to have been shallowing of the water during an intermediate period. In 71/9 only this shallowing is associated with a cool water fauna. There is no micropalaeontological evidence to indicate whether or not this shallowing is contemporaneous between each sequence. The microfauna from the shallow water sequence in Borehole 71/9 is influenced by temperature conditions, whilst that from the deeper water sequence of Borehole 71/10 is not so affected. The present sea floor in the area of Borehole 71/9 appears to be undergoing active deposition whereas around Borehole 71/10 the evidence suggests non-deposition.

## Appendix 5: The Organic Geochemistry of some Modern Sediments from the Sea of the Hebrides by B. Cooper

Thirty one samples of surface and core sediment, providing a representative selection of sediment from the area, were received. To date fifteen sediment samples have been extracted for their soluble organic content and subsequently fractionated to give aliphatic hydrocarbons and fatty acids. Extractabilities were low (75-225 p.p.m.) and alkanes made up between 2 and 50 per cent of the extracts. Alkenes and sulphur, ubiquitous in near shore sediments, were absent.

Analysis by gas-liquid chromatography showed the alkanes to be complex mixtures from which n-alkanes, pristane and phytane were particularly prominent. It was possible to recognise associations of alkanes; for example, the n-alkanes with 33, 31, 29, 27 and 25 carbon atoms were on occasion in greater concentration than their neighbours and can be ascribed to their derivation from the cuticle wax of land plants. Other groups of n-alkanes appeared to be regularly distributed about haxacosane (C-26), heneicosane (C-21), and heptadecane (C-17) with which pristane and phytane were associated.

The origin of the alkanes appears to be bacterial rather than algal and the fatty acids are being analysed to further elucidate the relation between nature of the organic matter and depositional environment.

## ppendix 6: Project Details

*romagnetic Survey, 1962 to 1964*

Aeromagnetic surveys have been flown over whole of Great Britain, Northern Ireland d adjacent sea areas, although in the present ea coverage does not extend west of 08° 00' W.

Surveys over the Sea of the Hebrides were wn with an east-west flight line separation of m and a tie-line separation of 10 km; mean rain clearance was 305 m and positions were ed by photograph over land and by Main Chain cca over the sea. Results for the present ea have been published previously at 1:250 000 ale as Sheets 10 and 12 of the Aeromagnetic p of Great Britain and Northern Ireland, tional Grid Diagram Edition.

*R.S. John Murray, 20.9.68 to 3.11.68*

This cruise was almost entirely geophysical, ans for sampling work being severely hampered failure of the ship's hydraulic winches and by verse weather.

A survey was made of 4940 km of geophysical e, 60 per cent in the present area, (Fig. 1). ong the majority of lines, gravity was easured with an Askania GSS-2 Gravity Meter d magnetic field with a Varian proton magneto- eter. Seismic reflection studies were made th an E. G. and G. sparker profiling system. a few localities a 5 kHz pinger and a dual de-scanning sonar were operated. A report cruise details and equipment is available in arine Geophysics Unit Report No. 28. In dition, sediment samples were taken at 27 ations using a Shipek grab, and one sample solid rock was recovered by the Institute's vers.

Position fixing by Main Chain Decca, radar d visual fixes was generally of poor quality e to considerable random variation in Decca gnals. This has led to many problems in bsequent data processing, most of which ve been adequately, though laboriously solved.

*.v. Maria W, 25.7.69 to 27.8.69*

Rock and sediment samples were taken at e hundred and eighty-one stations controlled the geophysical traverses run by R.R.S. hn Murray.

The work was undertaken by George Wimpey Co using the following equipment: Wimpey- pine Pneumatic Vibrocorer; IGS Hull-type avity Corer with rock and sediment barrels; ck and sediment dredges; Shipek grab; Spirotechnique Underwater Television System; Harrison Hard-Rock Drill. Position fixing was by Main Chain Decca.

*Deep Seismic Reflection Survey, 1969*

In 1969, a contract was placed with Seismograph Service (England) Ltd. of Holwood, Keston, Kent, to undertake a marine seismic investigation in the Sea of the Hebrides, the Minches and the approaches to the Clyde Estuary. Between 12 August and 14 October about 1000 km were surveyed using seisprobe gas exploders and a 24-section geophone streamer 1668 m long, coupled to a digital recording system operated at a 4 millisecond sampling rate. Shooting 57.5 pops per km allowed 48-fold coverage, four adjacent traces being then combined (vertical stack) to a summed trace, subsequent processing providing a horizontal 12-fold stack. Not all parts of all lines were processed because field sections and preliminary processing had indicated that parts of some lines would provide no reflection data. In Fig. 1, lines within the present area are shown for which processed sections have been prepared.

Decca Hifix positioning was used throughout the survey.

*M. v. Vickers Venturer and Pisces, 1.6.70 to 10.6.70*

As part of an extended evaluation of the submersible 'Vickers Pisces' twenty reconnaissance dives were made on representative topographic features (Eden and others, 1971). Three samples of solid were recovered, two with the submersible's handling arm and one with a Harrison Hard-Rock Drill attached to the torpedo claw of the submersible.

*M. v. Surveyor, 4.9.70 to 14.10.70*

About 2750 km of line were surveyed using a La-Coste Romberg Air-Sea Gravity Meter, Varian Proton Magnetometer and E. G. and G. Sparker Profiling System. The area of the survey extended westwards from Colonsay and Mull to the top of the continental slope.

With the cooperation of the Hydrographic Department of the Ministry of Defence (Navy) a Decca Hifix Chain set up for naval work was utilised by the Institute. This gave excellent positioning reliability.

The project is described in Marine Geophysics Unit Report No. 14.

*M. v. Vickers Venturer, 4.9.70 to 27.9.70*

Following the work with Pisces in June 1970 Vickers Venturer was remobilised to undertake

Table 2. Geological and geophysical projects in the Sea of the Hebrides

| Date | Project | Ship |
|---|---|---|
| 1962-1964 | Aeromagnetic survey | |
| 20.9.68 to 3.11.68 | Shallow seismic reflection survey. Gravity survey. Magnetic survey. Sonar survey. Sediment sampling | R.R.S. John Murray |
| 25.7.69 to 27.8.69 | Rock and sediment sampling | M.v. Maria W |
| 12.8.69 to 14.10.69 | Deep seismic reflection survey | |
| 1.6.70 to 10.6.70 | Observation. Rock and sediment sampling | M.v. Vickers Venturer and Pisces |
| 4.9.70 to 14.10.70 | Shallow seismic reflection survey. Gravity survey. Magnetic survey | M.v. Surveyor |
| 4.9.70 to 27.9.70 | Shallow seismic reflection survey. Rock and sediment sampling. Sonar survey | M.v. Vickers Venturer |
| 9.3.71 to 1.4.71 | Over-the-side drilling. Sediment sampling | M.v. Whitethorn |
| 20.6.71 and 21.6.71 | Observation. Rock and sediment sampling | M.v. Vickers Venturer and Pisces |
| 21.8.71 to 17.9.71 | Rock and sediment sampling. Sonar survey. Sea-bed scintillation probe trials | M.v. Surveyor |
| 27.9.71 to 1.10.72 | Sediment sampling by divers | |

sediment and rock sampling and submarine photography. The following equipment was used: IGS '10-ft' Electric Vibrocorer; IGS Gravity Corer with rock and sediment barrels; Shipek grab; Spirotechnique Underwater Television System.

Sediment sampling formed the major part of the daytime programme, 253 stations being occupied in an area extending from Skye south-westwards to Barra Head and Colonsay.

In addition the ship carried an E. G. and G. Sparker Profiling System and a Kelvin Hughes Transit Sonar which were used at night to complement the 1968 geophysical work in areas where additional control was needed. About 1000 km of survey were run. Position fixing was by Decca Hifix when operational, otherwise by Main Chain Decca or Radar.

*M.v. Whitethorn, 9.3.71 to 1.4.71*

Drilling, using shell and auger and rotary drilling methods (Chesher and others, 1972; Barton, 1971), recovered cores of solid rock from two sites and provided important information about the nature of the drift. Bad weather throughout the period of operation prevented further drilling, but sediment sampling was continued in sheltered areas, using the Wimpey-Alpine Vibrocorer, and IGS Gravity Corer and a Shipek grab.

Position fixing was by Alpine Precision Radar and Main Chain Decca.

*M.v. Vickers Venturer and Pisces, 20.6.71 and 21.6.71*

As part of a programme in the Irish Sea and off Western Scotland (Eden and others, 1973) three dives were made in the present area on 20 and 21 June. A sample was cored from the Blackstones Bank using a Harrison Hard-Rock Drill fitted to the submersible and two localities off the east coast of the Outer Hebrides were examined.

*M.v. Surveyor, 21.8.71 to 17.9.71*

One hundred and sixty-seven sediment stations were occupied in the area covered by the 1970 (m. v. Surveyor) geophysical survey, using an IGS gravity corer and a Shipek grab. At three stations solid rock was recovered by the Institute's divers and at a further two by the IGS Midi Drill (Eden and Ardus, 1972).

Traverses with a Kelvin Hughes Transit Sonar were run in conjunction with the sampling and trials were made of a towed sea-bed scintillation probe developed by the United Kingdom Atomic Energy Authority and IGS Geochemical Division.

Positioning was by Decca Hifix when this was operational, otherwise by Main Chain Decca.

*Diving Project, Mull, 27.9.71 to 1.10.71*

In order to investigate the magnetite content of modern sands and silts around the Mull plutonic centre five sampling traverses were made by divers. These traverses, in Salen Bay, Loch Buie, Carsaig Bay and Loch Scridain, were chosen to represent the various inshore environments around the centre.

Sample stations were controlled by Marconi Ferrograph echo-sounder traverses run with a Zodiac inflatable. At each a jar and a 0.5 m core sample were taken. Stations were marked by buoys, the positions of which were fixed by sextant from shore.

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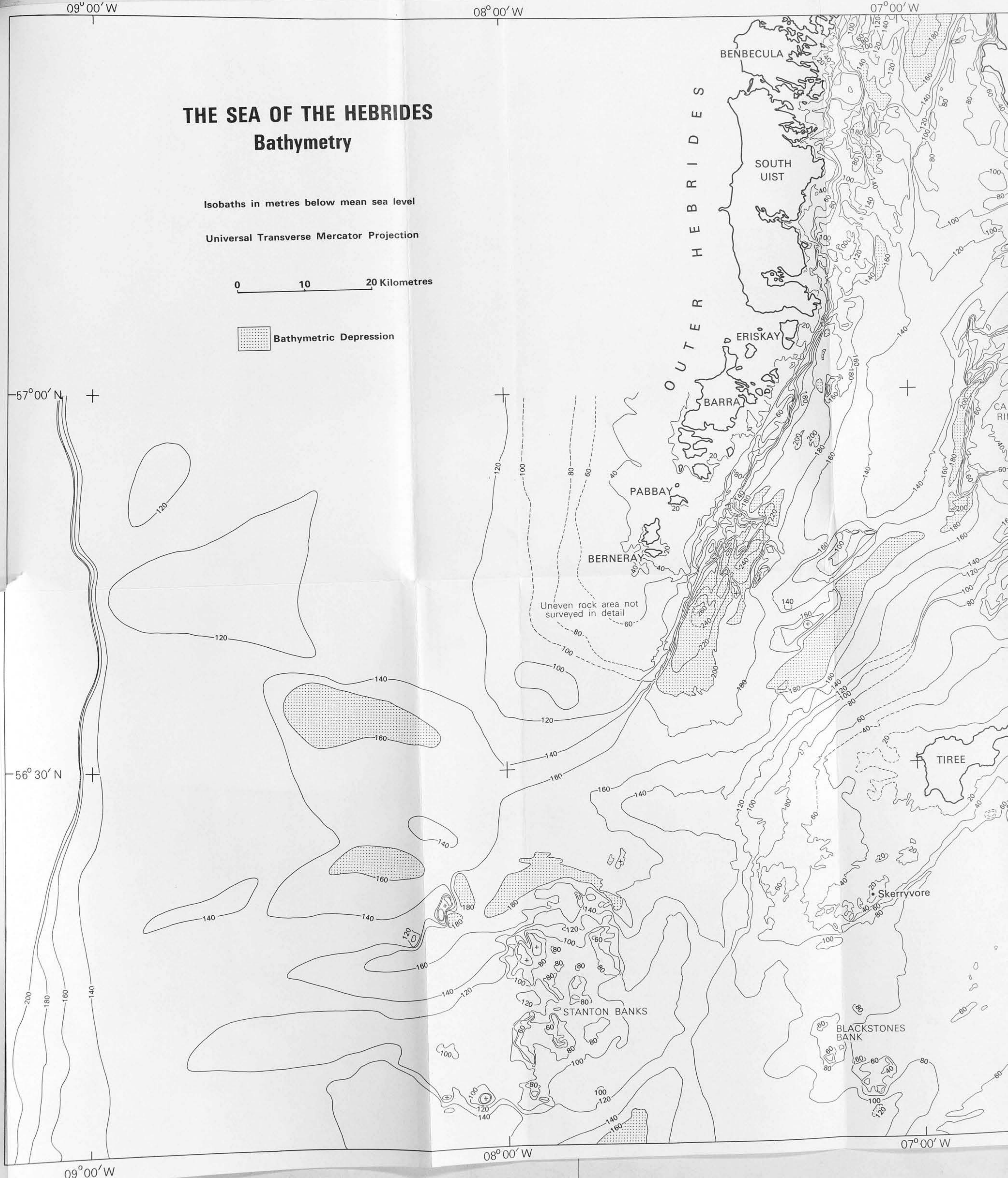
THE SEA OF THE HEBRIDES
Bathymetry
Isobaths in metres below mean sea level
Universal Transverse Mercator Projection
0 10 20 Kilometres
Bathymetric Depression
09° 00′ W
08° 00′ W
07° 00′ W
57° 00′ N
56° 30′ N
BENBECULA
SOUTH UIST
OUTER HEBRIDES
ERISKAY
BARRA
PABBAY
BERNERAY
Uneven rock area not surveyed in detail
TIREE
Skerryvore
STANTON BANKS
BLACKSTONES BANK

07°00′W
06°00′W
57°00′N
56°30′N
OUTER HEBRIDES
BENBECULA
SOUTH UIST
ERISKAY
BARRA
PABBAY
BERNERAY
SKYE
SLEAT
CANNA
RHUM
CANNA RIDGE
EIGG
MUCK
Sound of Arisaig
HAWES BANK
ARDNAMURCHAN
Loch Sunart
COLL
Sound of Mull
TIREE
MULL
LORNE
IONA
Skerryvore
BLACKSTONES BANK
Dubh Artach
COLONSAY
JURA
ON BANKS
COMPLEX SYSTEM OF TROUGHS AND RIDGES TRENDING N.E.-S.W.
ck area not
in detail

07°00´W
06°00´W
57°00´N
56°30´N
OUTER HEBRIDES
BENBECULA
SOUTH UIST
BARRA
PABBAY
BERNERAY
SKYE
RAASAY
Red Hills (Acid) Plutonic Centre
Cuillins (Basic) Plutonic Centre
SLEAT
Sound of Sleat
MOINE THRUST
STRATHCONON FAULT
CANNA
CANNA RIDGE
Oigh-sgeir Light
RHUM
Rhum Plutonic Centre
Borehole 71/10
EIGG
MUCK
HAWES BANK
Ardnamurchan Plutonic Centre
COLL
TIREE
Skerryvore Light
MULL
Mull Plutonic Centre
MORVERN
LORNE
Firth of Lorne
GREAT GLEN FAULT
LOCH ASSAPOL FAULT
CAMASUNARY FAULT
CAMASUNARY-SKERRYVORE FAULT
THE MINCH FAULT
EASTERN MARGIN OF THICK SEDIMENTS
Dubh Artach Light
Blackstones Plutonic Centre
COLONSAY
Borehole 71/9
JURA
Rockhead at least 280m below m.s.l.
Deeper than 220m in places
Rockhead at least 140m below m.s.l.
Rockhead 180m below m.s.l. in places
Rockhead 300m below m.s.l. in places
Rockhead at least 180m below m.s.l.
Rockhead at least 200m below m.s.l.
Rockhead at least 380m below m.s.l.
Rockhead at least 200m below m.s.l.
SH206
SH207
SH119
SH175
SH177
SH133
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SH28
SH226
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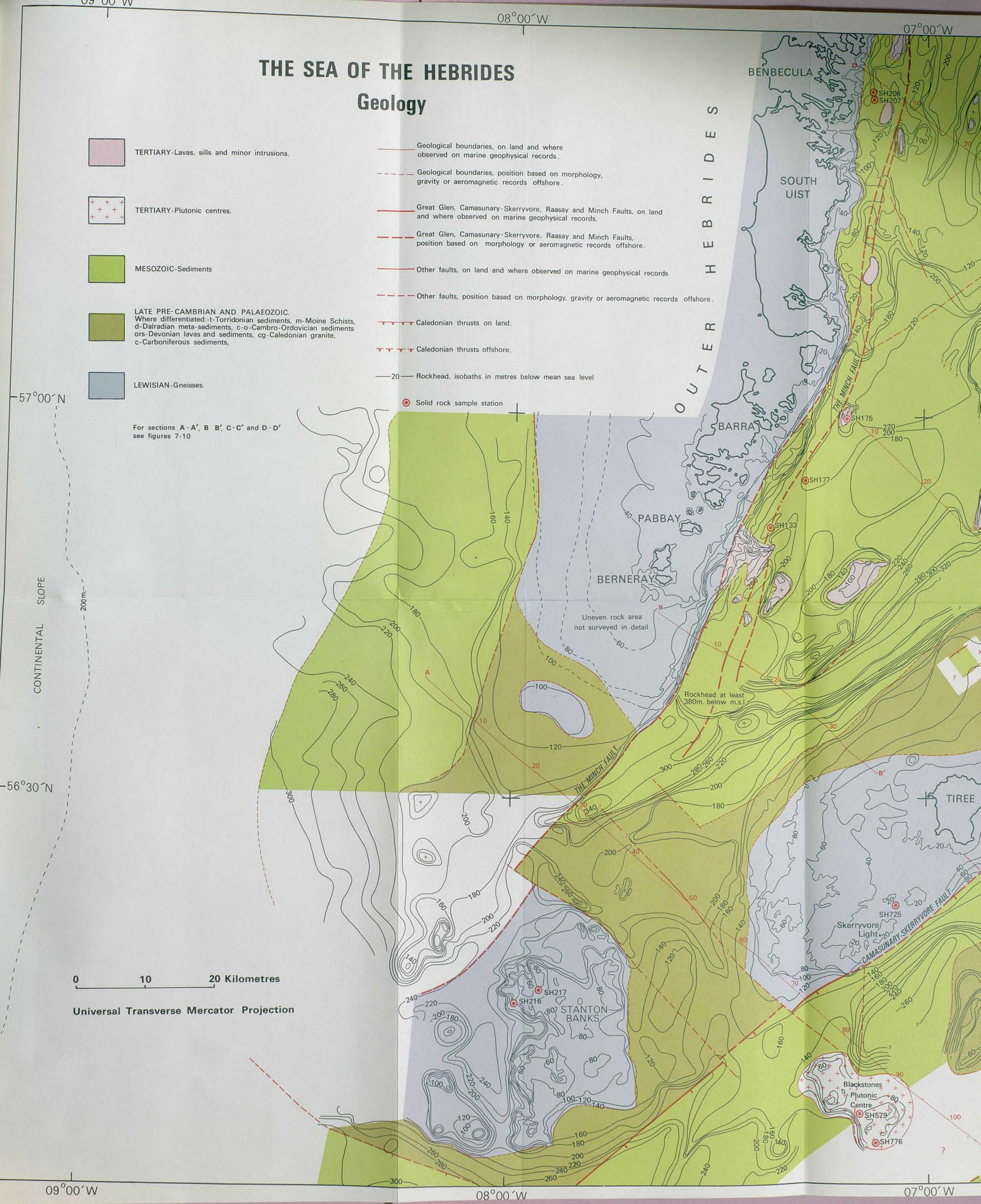
SH529
SH776
SH237


THE SEA OF THE HEBRIDES
Geology
TERTIARY-Lavas, sills and minor intrusions.
TERTIARY-Plutonic centres.
MESOZOIC-Sediments
LATE PRE-CAMBRIAN AND PALAEOZOIC. Where differentiated:-t-Torridonian sediments, m-Moine Schists, d-Dalradian meta-sediments, c-o-Cambro-Ordovician sediments ors-Devonian lavas and sediments, cg-Caledonian granite, c-Carboniferous sediments.
LEWISIAN-Gneisses.
For sections A-A', B B', C-C' and D-D' see figures 7-10
Geological boundaries, on land and where observed on marine geophysical records.
Geological boundaries, position based on morphology, gravity or aeromagnetic records offshore.
Great Glen, Camasunary-Skerryvore, Raasay and Minch Faults, on land and where observed on marine geophysical records.
Great Glen, Camasunary-Skerryvore, Raasay and Minch Faults, position based on morphology or aeromagnetic records offshore.
Other faults, on land and where observed on marine geophysical records
Other faults, position based on morphology, gravity or aeromagnetic records offshore.
Caledonian thrusts on land.
Caledonian thrusts offshore.
20 Rockhead, isobaths in metres below mean sea level
Solid rock sample station
08°00'W
07°00'W
09°00'W
57°00'N
56°30'N
OUTER HEBRIDES
BENBECULA
SOUTH UIST
BARRA
PABBAY
BERNERAY
TIREE
STANTON BANKS
THE MINCH FAULT
CAMASUNARY-SKERRYVORE FAULT
CONTINENTAL SLOPE
200m
Uneven rock area not surveyed in detail
Rockhead at least 380m. below m.s.l.
Skerryvore Light
Blackstones Plutonic Centre
SH206
SH207
SH175
SH177
SH133
SH725
SH216
SH217
SH579
SH776
0 10 20 Kilometres
Universal Transverse Mercator Projection

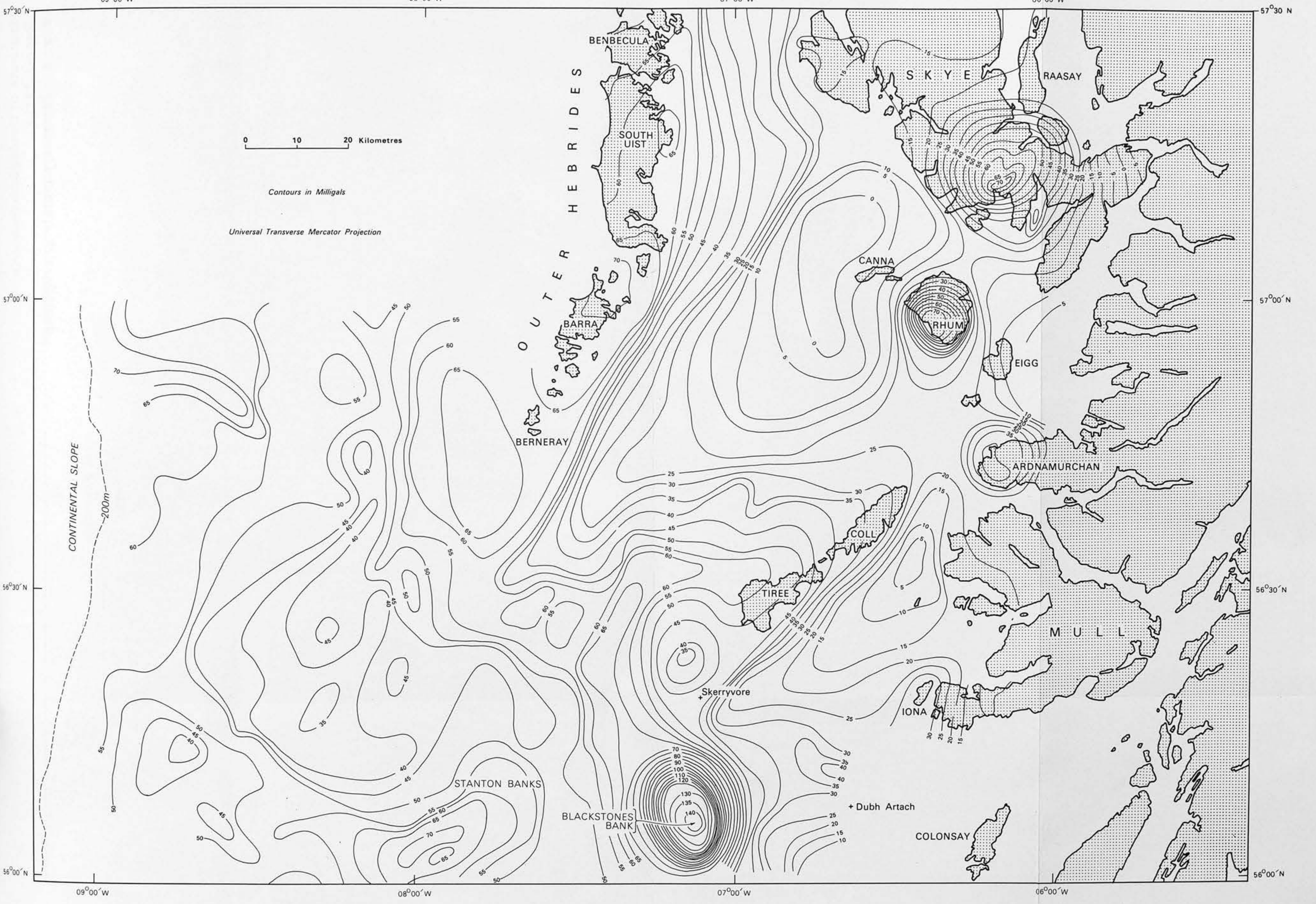



Fig. 5. Bouguer anomaly gravity map

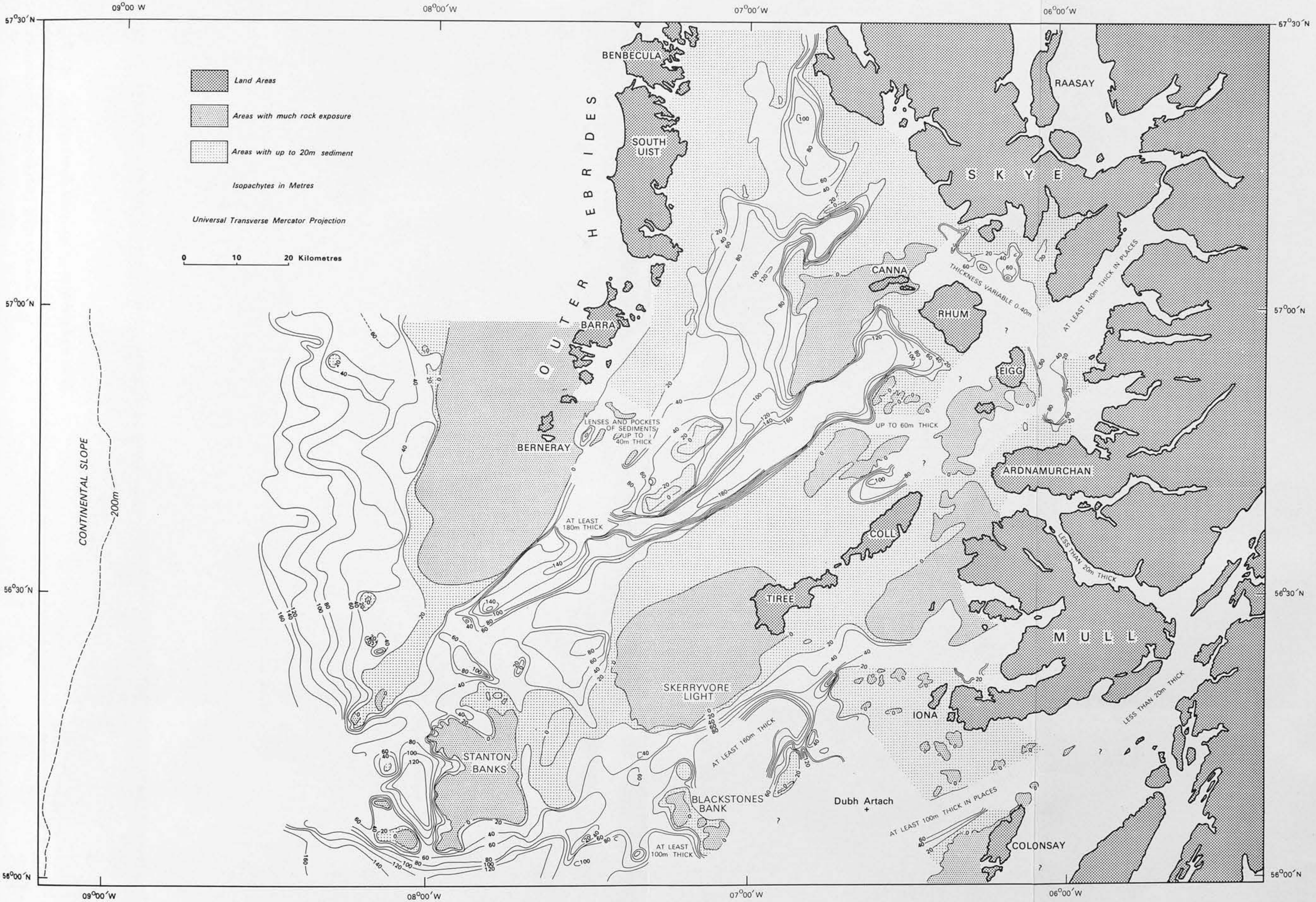



Fig. 6. Quaternary sediment isopachyte map

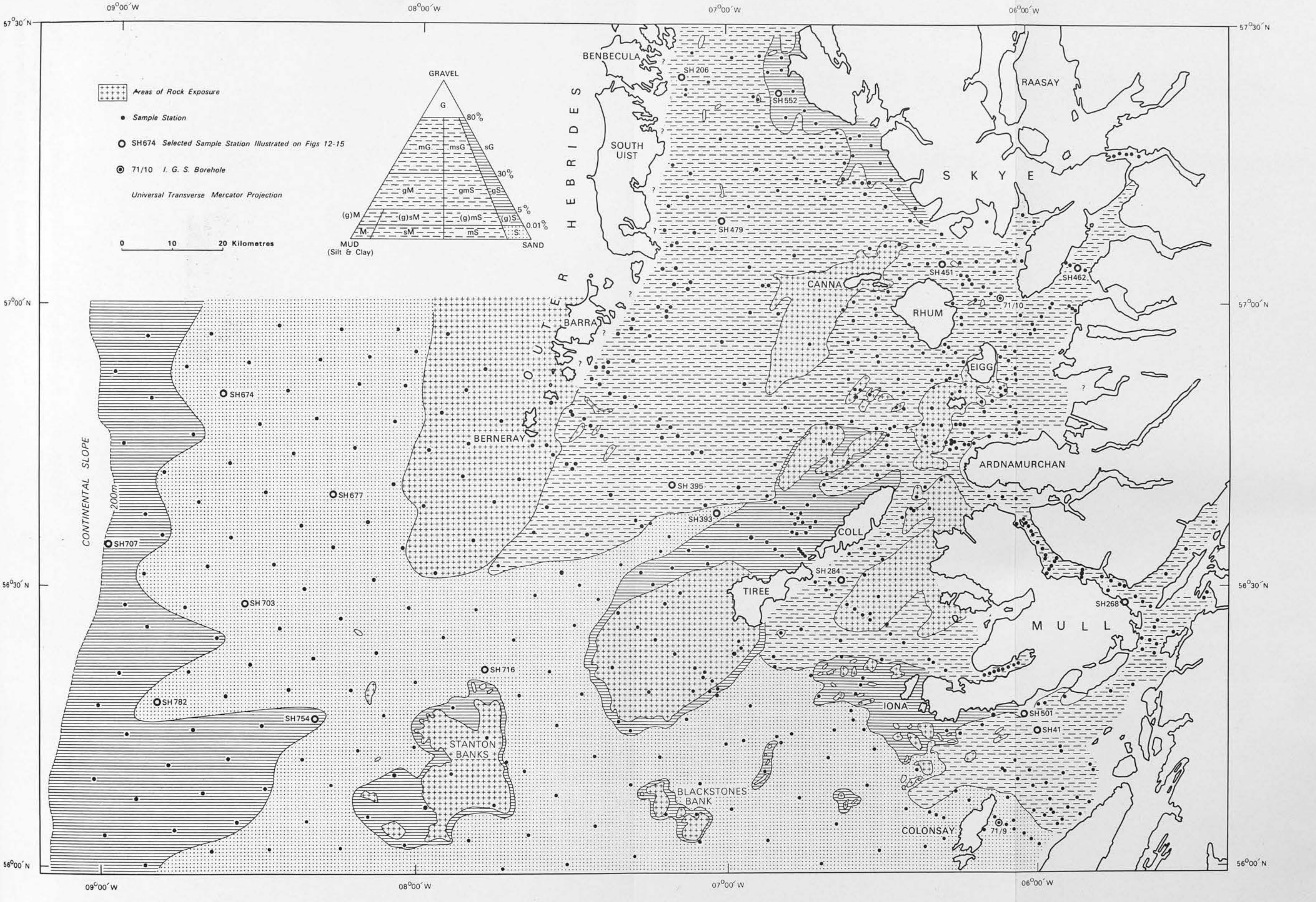



Fig. 11. Sea-floor-sediment and rock-exposure distribution

# BATHYMETRIC AND SCUBA DIVING SURVEYS ON HELEN'S REEF, ROCKALL

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* S. K. WILLIS, Institute of Oceanographic Sciences, Wormley, Godalming, Surrey, U.K.

With a contribution by R. K. HARRISON, Chief Petrographer, I.G.S.

## INTRODUCTION

Helen's Reef, like the adjacent Island of Rockall, is the top of a rock ridge rising from the continental shelf depths of the Rockall Bank 420km. west of the Scottish mainland (Fig. 1). It was first recorded in the middle of the eighteenth century by a Lieutenant des Vaisseaux de Kerguelen Trémarée (quoted in Fisher, 1956, p. 20) who described it as "a submerged rock over which the water breaks", a description confirmed by our own observations. The Reef is marked in all weathers by an area of white water not more than 30m. across; this is caused by the swell breaking over a small rounded rock which is visible in the troughs of the larger waves. The Reef is named after the Dundee Brigantine *Helen* which in 1824 struck the Reef and sank with the loss of 16 lives.

Work on the geology of Rockall Island itself (Lacroix, 1921, 1923; Sabine, 1960; Hawkes, *et al.*, in press) has shown it to be composed of aegirene granite with acmite and riebeckite. This rock has yielded an isotopic ($^{40}Ar/^{40}K$) date of 60±10m.y. (Miller and Mohr, 1965) and it can therefore be included in the North Atlantic Tertiary igneous province.

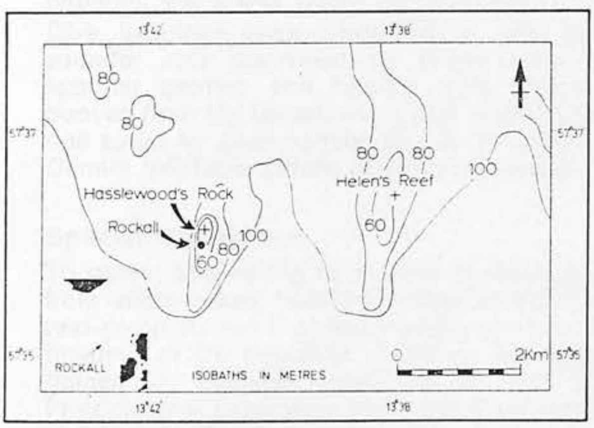


*Figure 1.* The Rockall area.

Indications that Rockall formed part of a plutonic centre came in 1969 when the Hydrographic Department (M.O.D.) made a detailed bathymetric and shipborne magnetic survey of the Rockall area. Roberts (1969) pointed out that the magnetic anomalies (Fig. 2) were similar to those observed over the Tertiary plutonic centres of the Hebrides.

Figure 2 shows an acurate belt of high amplitude anomalies enclosing an area of low amplitude anomalies; within the latter lies Rockall Island, Helen's Reef, which lies within the belt of high anomalies, has a significant anomaly associated with it (Fig. 3). This suggests that, unlike Rockall Island, it is formed of a basic igneous rock and might be part of a ring dyke or cone sheet

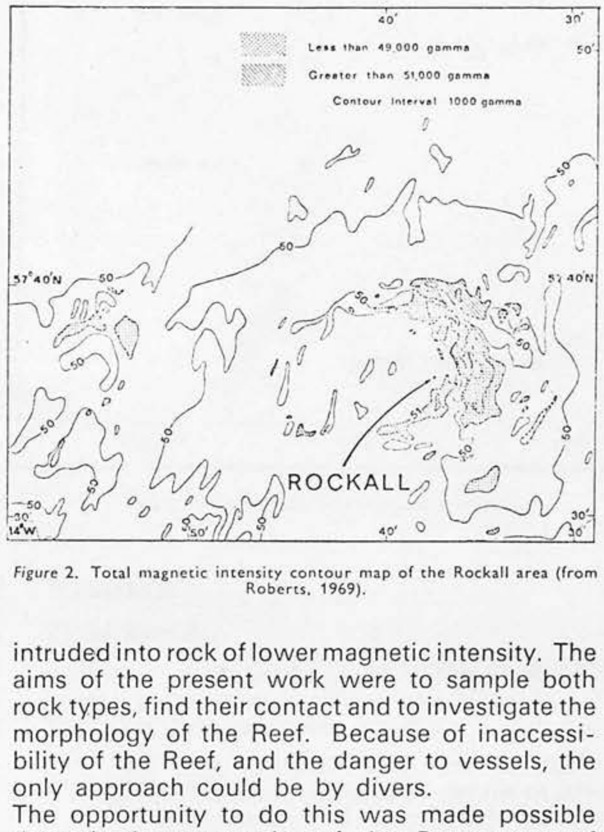


*Figure 2.* Total magnetic intensity contour map of the Rockall area (from Roberts, 1969).

intruded into rock of lower magnetic intensity. The aims of the present work were to sample both rock types, find their contact and to investigate the morphology of the Reef. Because of inaccessibility of the Reef, and the danger to vessels, the only approach could be by divers.

The opportunity to do this was made possible through the generosity of the Department of Trade and Industry who provided places for a diving team on the R.F.A. Helicopter Support Ship *Engadine;* the vessel being chartered by the Department to install a navigation beacon on Rockall Island. The team of six divers was drawn from the National Institute of Oceanography and the Institute of Geological Sciences, Scottish Continental Shelf Unit: and was led by Dr. N. C. Flemming. Lieutenant P. Willstead, R.N. was responsible for the bathymetric survey.

The *Engadine* left Plymouth on 16th June and returned to Portland on 30th June. The period of the work was chosen for having in the past, the mildest weather. In fact, conditions were so bad that they caused the abandonment of all pre-arranged plans and only one full day of work was achieved.

## METHODS

### Bathymetric Survey

The bathymetric survey was planned to be run from the *Engadine's* launch and positioned by Two-Range Decca Trisponder. One beacon was to be placed on Rockall and the second on a buoy north of the line from Rockall to Helen's Reef. With the Distance Measuring Unit installed on ths ship's boat, it was intended to run saturation soundings at 15m. intervals in a 0·75km. square centred on the Reef.

The planned detailed bathymetric survey of the area had to be abandoned due to inclement weather, and it was only possible to run the four traverses shown in Figure 3. These were carried out using the ship's launch, and positioning achieved by mounting a Trisponder beacon on the launch and measuring its distance from the *Engadine* and simultaneously taking its bearing relative to Rockall Islet. Fixes were synchronised with soundings by radio checks. Errors arising from this system are estimated to be in the range 20–50m.

### Rock Sampling

Diving from a small boat is the only feasible way of sampling the Reef, which is a hazard to larger ships carrying remote controlled sampling devices. The hardness of the rock prevented the use of light sampling equipment from a small boat.

The divers were equipped with hammer and cold chisel, compass, depth gauge, watch and writing board or tape-recorder. The divers were trained in the use of explosives either for blasting off small samples or exploding an area of rock to allow examination of rock structure. With the limited time available, however, only hammer and chisel were used; the rock proved extremely tough and for deeper work or if larger samples were required, explosives would be necessary.

Dive locations were controlled by the echo-sounder and positioned by single-range Trisponder reading and bearing. The site was buoyed from the launch and a pair of divers with one stand-by diver transferred into an attendant Gemini inflatable before entering the water.

### Special Equipment

To permit safe diving to a depth of 55m. so far from shore-based facilities a Comex two-man, two-compartment chamber was installed on the foredeck of the *Engadine*. Team members were trained in chamber operation by the R.N. Physiological Laboratory and medical equipment was installed by the ship's doctor.

## CONDITIONS

Diving was undertaken in a 2 to 3m. swell and a light sea. In the area of the rock, however, white water at times unpredictably rose to a greater height. Work was made difficult by the swell, which produced severe motion down to a depth of 15m., and was restricted to rock sampling. The current ellipse, which was interpolated from data obtained at a station some miles from Rockall, was expected to range from 0·3 to 0·8 knots. Observed currents exceeded this figure and were estimated to be between 0·5 to 1·0 knots. Underwater visibility was of the order of 15–20m.

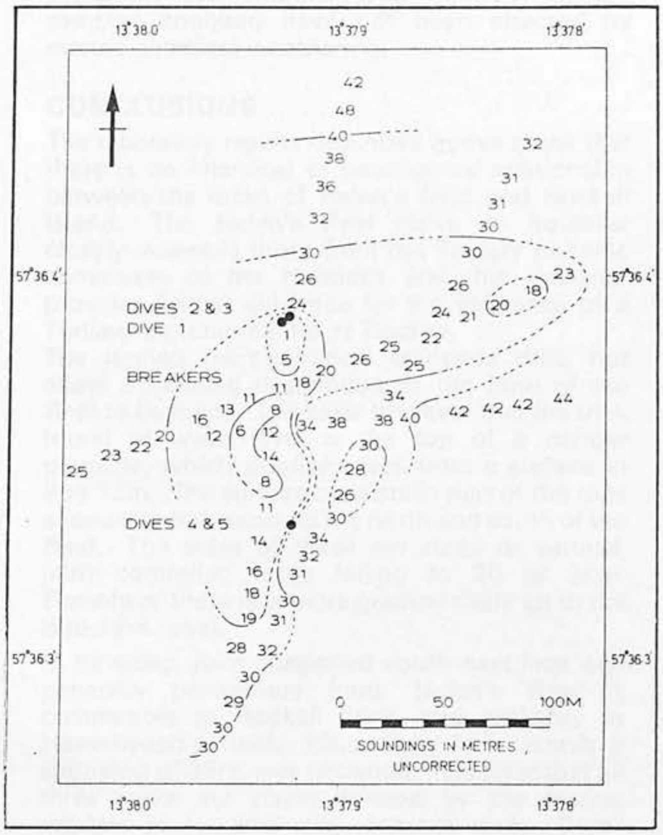


*Figure* 3. Helen's Reef. Soundings and dive locations.

## RESULTS

### Field Results

Five dives were made, three to the north of the breakers and two to the south (Fig. 3). The following features were common to all dives:

1. The rock sampled is a fine to medium grained basic igneous rock, details of which are given below. It is extremely hard and smooth; no weak or loose material is present; all corners are rounded. Rock-breaking was arduous and accounted for much of the time available under water, leaving little for observation.
2. Encrusting algae covered all rock surfaces. A thick growth of brown kelp was present at 10m.; it decreased in abundance with depth but was still common at 20m. Below 15m. Hydroids and Sea Anemones appeared.

### Dive 1

The shot rested on a narrow rock spur at 10m. Twelve small rock samples were taken from the crest of the spur and from its steep sided wall down to 15m. Jointing is not conspicuous, surfaces tending to be rounded rather than planar.

### Dive 2

The shot rested in a crevice running across a flattish rock platform at a depth of 10 to 12m. A rock sample was taken.

**Dive 3** (shot at same position as Dive 2)
Five samples were taken from 5m. down the vertical cliff beneath the rock platform. This cliff is joint controlled. Horizontal jointing gives rise to small ledges but apart from these the face falls shear to 17m.

**Dive 4**
A vertical, joint controlled cliff, striking S20°W, rises to a depth of 12m. At 17m. on the cliff face horizontal joint planes form a ledge. About 2–3kg. of small samples were taken from the area of the ledge.

**Dive 5** (shot at same position as Dive 4)
The cliff continues down beyond 29m., the deepest point reached. Horizontal, joint controlled ledges are common. At one point a columnar structure composed of vertical, 0·25× 0·25m. joint controlled columns of rock was observed.

**Laboratory results** (The following notes are provided by R. K. Harrison, Chief Petrographer, I.G.S.)
A ship-borne petrographical laboratory was installed on the ship to facilitate rapid analysis of the rock samples by means of thin microscopic sections. Results were relayed to the divers on site. The sections were produced by R. J. Merriman and M. T. Bizony. A full account of the results is given in Harrison, *et al.* (in press).
The dry samples have Munsell colour values near N3 (dark grey), speckled in the coarser varieties very light grey (N8). In average grain size, most of the fragments are slightly coarser (2·5mm.) than dolerite, yet finer than gabbro. Olivine-microgabbro is the commonest rock type, and consists of equant crystals of fresh, colourless olivine (forsterite near $Mg_{1\cdot6}Fe_{0\cdot4}SiO_4$),* and pale green to brown clinopyroxene (endiopside near $Ca_{0\cdot9}Mg_{0\cdot9}$ $(Si_{1\cdot9}Al_{0\cdot9})O_6$), set in a mesh of plagioclase laths (Bytownite $Ca_{0\cdot8}Na_{0\cdot2}Al_{1\cdot9}Si_2O_8$) with a little accessory chromian magnetite. The latter contains an unusually high amount of chromium up to 14 percent $Cr_2O_3$.
In the samples from the southern part of the reef, olivine-dolerite forms sharp contacts with the olivine-microgabbro into which it has been intruded. Here, olivine and clinopyroxene crystals (up to 1mm. across) are set in a fine-grained (0·2mm.), fluxioned groundmass of ragged pyroxene plates, olivine crystals, labradorite needles and specks of Cr-magnetite.
A third rock type is troctolitic, forming apparently local segregations of olivine and pyroxene (with subordinate plagioclase), but these may be a pointer to layered gravity-separated cumulates at greater depth.
Chemically, the olivine-microgabbro and olivine-dolerite are closely similar, indicating common derivation from a subalkaline olivine-basalt parent magma, and resemble other Tertiary gabbroic intrusions such as that recorded in St. Kilda (Harding, 1967). The magma therefore was totally unlike that forming the mid-Atlantic Ridge tholeiites. No chlorine was detected, so the samples analysed have not been affected by marine chemical weathering.

## CONCLUSIONS

The laboratory results described above show that there is no chemical or petrological relationship between the rocks of Helen's Reef and Rockall Island. The Helen's Reef rocks do however closely resemble those from the Tertiary plutonic complexes of the Hebrides and this similarity provides further evidence for the existence of a Tertiary plutonic centre at Rockall.
The limited morphological evidence does not allow a detailed description of the form of the Reef to be made. It is clear however that the rock found at wave level is the top of a narrow pinnacle, which possibly rises from a surface at 8 to 12m. The surface consists in part of the tops of spurs or buttresses to the north and south of the Reef. The sides of these are steep or vertical, joint controlled faces falling to 20 or 30m. Elsewhere there is a more gradual slope up to the 8 to 12m. level.

In its steep, joint controlled south-east face and generally precipitous form, Helen's Reef is comparable to Rockall itself, and probably to Hasselwood's Rock, 20m. away from which a sounding of 38m. was obtained. It is clear that all three rocks are stacks formed by the marine erosion of exceptionally resistant rock. Comparable stacks occur at St. Kilda where a Tertiary Centre which has suffered little glacial erosion is exposed to similar marine forces (Cockburn, 1935, p. 512 and Pl. III, Fig. 3). In contrast the erosion observed on the Blackstones Tertiary Centre, which lies within the limits of the Pleistocene ice sheet, is dominantly glacial although it, also, is exposed to the same marine conditions (Eden, *et al.*, 1971).

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*Mineral formulae here are based on electron microprobe analyses by Mrs. A. E. Tresham,

# THE ROLE OF DIVERS AND SUBMERSIBLES IN GEOLOGICAL MAPPING OF THE CONTINENTAL SHELF AROUND SCOTLAND, 1967–72

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## ABSTRACT

In the course of the reconnaissance of the U.K. Continental Shelf at present being undertaken by the Institute of Geological Sciences it has been found valuable to employ visual methods of sea bed examination at critical localities, particularly in the clear waters around Scotland where there are extensive exposures of bedrock.

Since the I.G.S. survey began in 1967, divers have carried out spot checks at many places both off the east coast and in the Sea of the Hebrides, detailed bedrock sections have been measured off south-eastern Scotland, and 37 observation and sampling dives have been made in deeper water with the submersible Vickers Pisces. These operations have been supplemented by the use of remote methods of visual observation, and have generally been undertaken as the final stage of a mapping programme based on geophysical traversing and shipboard sampling.

The value of different diving techniques in the overall project is discussed; the work has included studies of a submarine volcanic centre and outcrops of ancient basement rock off western Scotland, the top of the continental slope north of Ireland, scouring and deposition due to glaciation, and variation in sedimentation caused by degree of exposure to marine action.

The emphasis of the diving operations has been on examination of type localities from which conclusions can be extrapolated over wider areas by the use of remote methods.

## INTRODUCTION

The Institute of Geological Sciences has the task of compiling geological maps of the U.K. continental shelf using data from all sources, including commercial operators, other government groups, and from university and other research workers. The survey activities of the Institute itself constitute the framework within which geological information is assimilated into a comprehensive map.

The main I.G.S. marine survey effort proceeds in a number of well defined stages in each project area. The first stage is the collection of existing information, after which geophysical traversing is carried out on an 8km. grid, followed by sampling and drilling. At the sampling stage extensive use is made of visual methods of examining the sea bed by means of photography, divers and submersibles.

## THE ROLE OF DIVERS

### Detailed Traversing

When the I.G.S. marine survey was first getting under way in the mid 1960's, survey vessel time was very much more limited than at the present, and it was therefore convenient to devote some of the available scientific effort to taking an early opportunity to carry out a pilot geological diving project at Burnmouth, off the south-east coast of Scotland. This study (Eden, Carter and McKeown, 1969) involved very detailed geological measurements along three traverses, each about 300m. long, across a critical section of the sea bed on which are exposed steeply dipping strata absent in the coastal section due to a fault. Figure 1 illustrates the complexity of the problem—each of the thin rock layers shown had to be identified, described and sampled. In all 323 rock specimens were collected in the course of 80 man-hours of work in fairly shallow water, for the most part some 10 to 25m. deep. Visibility was normally

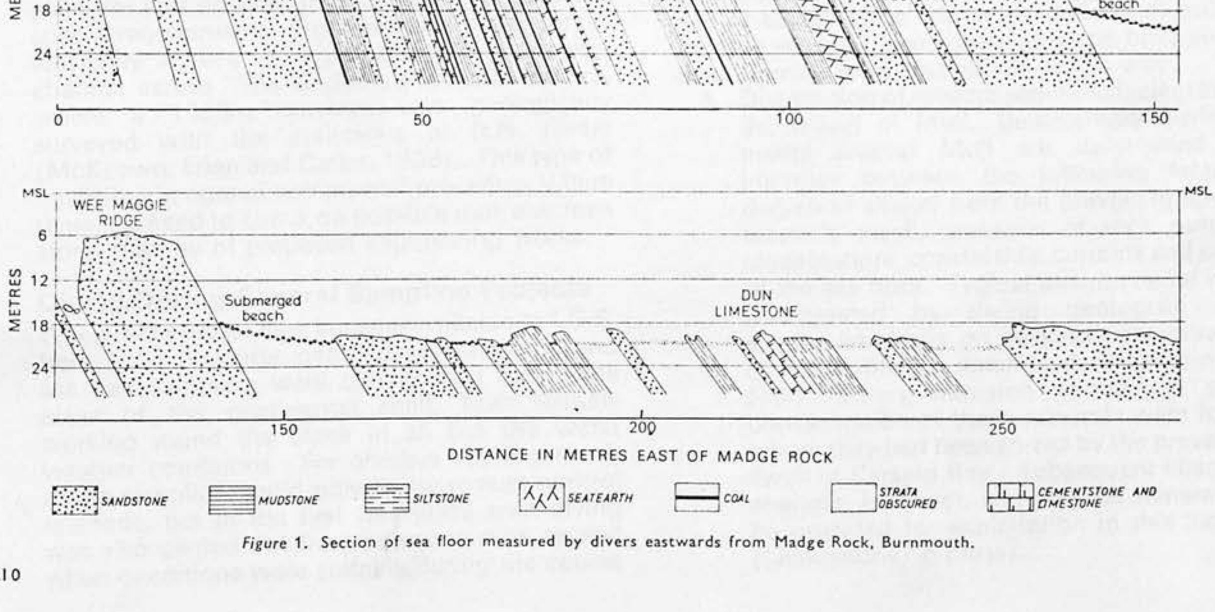


*Figure 1.* Section of sea floor measured by divers eastwards from Madge Rock, Burnmouth.

adequate, but variable on account of the open nature of the area, with no shelter at all to the east and north. Divers worked along pre-laid traverse lines, which had to be repeatedly replaced owing to disturbance by storms and other agencies. The work was carried out on a day basis from Edinburgh and was spread over a period of about two years, with considerable assistance from the Edinburgh branch of the B.S.A.C. in the early stages.

This study resulted in the compilation of a section which is unique and which appears to represent the only possible solution to this particular problem, since a borehole which later penetrated the same strata on the coast a few miles farther south encountered a sequence in which many of the important fossiliferous horizons found underwater are missing, being represented by sandstone into which they pass laterally. Some day, therefore, it will be worth while to go back to the Burnmouth section and make more comprehensive collections from the fossil beds for scientific study, as only one or two small samples have so far been taken from each.

Here, however, we come to the crux of the matter, which is that this sort of detailed work is only feasible under the direction of a diver who has a thorough knowledge of the geological issues involved. There are not many professional marine geologists available, and most of those who can dive are so heavily involved in the direction of general or economic survey projects that there simply is not time to devote to detailed scientific traversing from which there is no prospect of immediate economic benefit. It would be nice to think that the diving community could help here, but useful results in a Burnmouth-type situation can only be achieved by amateur geologist-divers in cases where a great deal of painstaking effort is forthcoming, knowing that in the end this is likely to produce a collection of rock fragments which may be of specialist scientific interest, but which to the layman look rather uninspiring.

At all events, for the time being I.G.S. is unlikely to repeat the Burnmouth experience in anything like the same degree of detail. There is, however, a place for less detailed traversing where there are special requirements. One such case arose during feasibility studies for a proposed new shipping channel across "The Bridge", Plymouth Sound, where a 1200m. traverse was geologically surveyed with the assistance of R.N. divers (McKeown, Eden and Carter, 1968). This type of traversing is normal commercial procedure where there is a need to check on possible rock outcrops along the line of proposed engineering works.

### Diving During General Sampling Projects

When more vessel time became available to I.G.S. from 1968 onwards, geophysical traversing and sea bed sampling were commenced over wide areas of the continental shelf, from vessels working round the clock in all but the worst weather conditions. For obvious reasons much of the sampling could only be by remote control methods, but in the first few years spot diving was also carried out from survey vessels as and when conditions were suitable during the course of routine sampling activities. Although general survey work is often in water too deep for anything other than special project diving, off western Scotland in particular a number of geologically important reefs rise to less than 30m. In such cases the practice was adopted of laying a shot on the reef, then diving down the shot from an inflatable whilst the mother vessel stood by. In this way important observations were possible and samples were obtained on Blackstones Bank igneous complex, Maxwell Bank, Skerryvore Bank, Hawes Bank and off the Outer Hebrides.

It soon became apparent, however, that there are major difficulties in diving from a general purpose sampling vessel. Firstly, it disrupts staff duty rosters, which have to be geared to 24-hour working; secondly, it involves always carrying enough divers to make up a minimum team even when there is no diving; thirdly, the remainder of the scientific team on the mother ship is unable to operate whilst the vessel stands by for the divers; fourthly, the geologist in charge has to divide his efforts between two full time activities—diving with the diving team and directing the rest of the vessel's scientific work; fifthly, it is difficult to keep the team in training during a long period at sea with only fortnightly port calls and with changing personnel. The last two of these considerations potentially effect safety, and are the reasons why this type of operation is no longer normally carried out by I.G.S. This decision has been taken with regret because there is no doubt that a geologist free swimming on the sea bed, able to work almost as on land, is a most effective agent for geological studies.

### Special Projects

Following the decision that detailed traversing is too time consuming and that spot diving from survey vessels normally involves unacceptable penalties, I.G.S. has adopted the policy of mounting periodical special local diving projects with suitable small vessel support. Some of these are on a day basis aimed at keeping the diving group together and in training, others last up to about a week. The project objectives are related to the special contribution which divers are able to make to close work, particularly at the inshore end of survey areas which are difficult of access to large vessels. Three main subjects have so far been chosen for investigation in this way:

1. Distribution of modern sediment facies round the Island of Mull. Sedimentary environments around Mull are determined by interplay between the following factors: degree of shelter from the prevailing southwesterly swell, presence of rock outcrop close inshore, coastal tidal currents and slope of the sea floor. Typical environments were investigated by diving geologists with special emphasis on seeking concentration of magnetitie or ilmenite derived from the Mull Tertiary intrusion centre. A small concentration of these minerals were found where they had been sorted by the prevailing swell in Carsaig Bay. Subsequent chemical analysis, however, showed the minerals to be unsuited for exploitation in this locality (Livingstone, in press).

2. Submarine erosion levels around Scotland. A well defined post-glacial beach has been located at depths of 10 to 20m. in the Firth of Forth, sloping upwards towards central Scotland. There are suggestions of similar erosion levels off the west coast. The evidence fits well with the sequence of events which might be expected to have occurred in post-glacial times, but the evidence is scattered and it is difficult to date the levels in some areas.
3. Identification of inshore rock exposures off the shores of the Moray Firth. There are extensive bed rock exposures in coastal waters down to depths of about 30m. These have been sampled at about a dozen localities between Brora and Buckie, yielding material related to the coastal Permian and Mesozoic strata, which thicken seawards to form a thick basin occupying most of the offshore area.

These projects have been run by a team of five divers, four of which are geologists, at I.G.S., Edinburgh. The existence of this group has a useful spin-off in providing I.G.S. with a nucleus of scientists who are thoroughly familiar with sea bed geological conditions, thus assisting a proper appreciation of the meaning of geophysical and remote sampling indications. The group also provides support for geological equipment development when underwater observation or adjustment is required, and a facility for attempting, in suitable conditions, recovery of sampling gear which has been lost or caught up on the sea bed—this last function alone has more than repaid the cost of the group's activities in recent years.

## MANNED SUBMERSIBLES

The first British manned submersible capable of working in open sea conditions on a routine basis was Vickers Pisces, which became operational in 1969. The Natural Environment Research Council, of which I.G.S. is a component body, commissioned the submersible's first contract in the autumn of that year, in the course of which a mixed group of research scientists evaluated the potential of the basic vehicle, with very few external handling tools, in dives off Oban and in Lower Loch Fyne. This experimental work was discussed in a joint summary published by N.E.R.C. in 1970. Since then I.G.S. has carried out two geological projects, totalling 37 dives, with Vickers Pisces working off the west Scottish coast and in the Irish Sea (Eden, *et al.*, 1971, Eden, *et al.*, 1973)

It is fair to say that these activities were in the first place experimental, but after three seasons the question needs to be faced as to whether the geological results justify the financial outlay, which is considerable, about double that of operations with a standard geological sampling vessel.

The length of dives in terms of time on the sea bed has averaged 3 hours, 15 minutes. For 23 dives two geologist observers were carried, partly for training in techniques, but for the 1971 programme only one working geologist accompanied the single pilot. External cameras and closed circuit T.V. have been used from the start, and sampling devices have now been developed which permit efficient collection of solid rock and sediment samples. Dive locations have ranged from shallow sheltered sites in lochs, to the top of the continental slope 90km. west-south-west of the southern end of the Outer Hebrides, where a depth of 380m. was reached; they have included many offshore rocky shoals and the deepest depression in the British Continental Shelf—323m. below O.D. in the Inner Sound of Raasay. It is a tribute to the operators that on not one occasion was a dive cancelled on account of weather, although at times planned alternative sites in more sheltered locations had to be used.

The result of these dives has been the compilation of a considerable dossier on the composition and appearance of the sea bed off north-west Britain; this has assisted consideration of geological structure and of past and present processes of erosion and sedimentation. Underwater visibility has varied from about 3m. to some 50m.; normally backscatter from the headlights has limited vision to 6 or 7m., quite adequate for the observer to make a thorough examination, take good quality photographs and collect samples.

The overall picture which has emerged is one of great variety, with a number of contrasting sea bed environments. The central parts of the well known glacially overdeepened hollows of western Scotland are floored by plains of brownish-grey soft bioturbated mud, with abundant "sea pens" and burrows of *Calocaris* and *Nephrops;* in Lower Loch Fyne manganese nodules were observed being ploughed up to the surface by these organisms, a process which had been previously suspected but not observed. Away from the central parts of the hollows a widespread scatter of morainic detritus is to be seen, in course of submergence in accumulating mud. By searching amongst the boulders on rises, flat exposures of underlying bedrock can sometimes be located and sampled. Bounding slopes of the glaciated hollows include impressive rock walls (Fig. 2), with local overhangs and in places with large ice rafted boulders perched precariously on narrow ledges.

At the top of the continental slope the dominant sea bed type comprises a cobble gravel pavement with scattered boulders, forming a thin crust over glacio-marine deposits which constitute a major western "end moraine" of Pleistocene glaciation. The cobble gravel has clearly been winnowed by a lower sea level, the only mobile material at the present time being thin patches and streamers of ripple marked sand, moving northwards along the contour where observed.

Similar immobile cobble gravel pavements occur around glaciated knolls of Lewisian, Torridonian and Tertiary igneous rock closer inshore. Moving across the cobble pavements are large, well formed, fresh sand waves composed mainly of shell detritus; these are particularly pronounced in areas of strong currents.

A practical facility provided by Vickers Pisces is the ability to sample exposed solid rock in vertical cliffs and in rock pavements strewn with glacial detritus. Maps of solid geology depend on

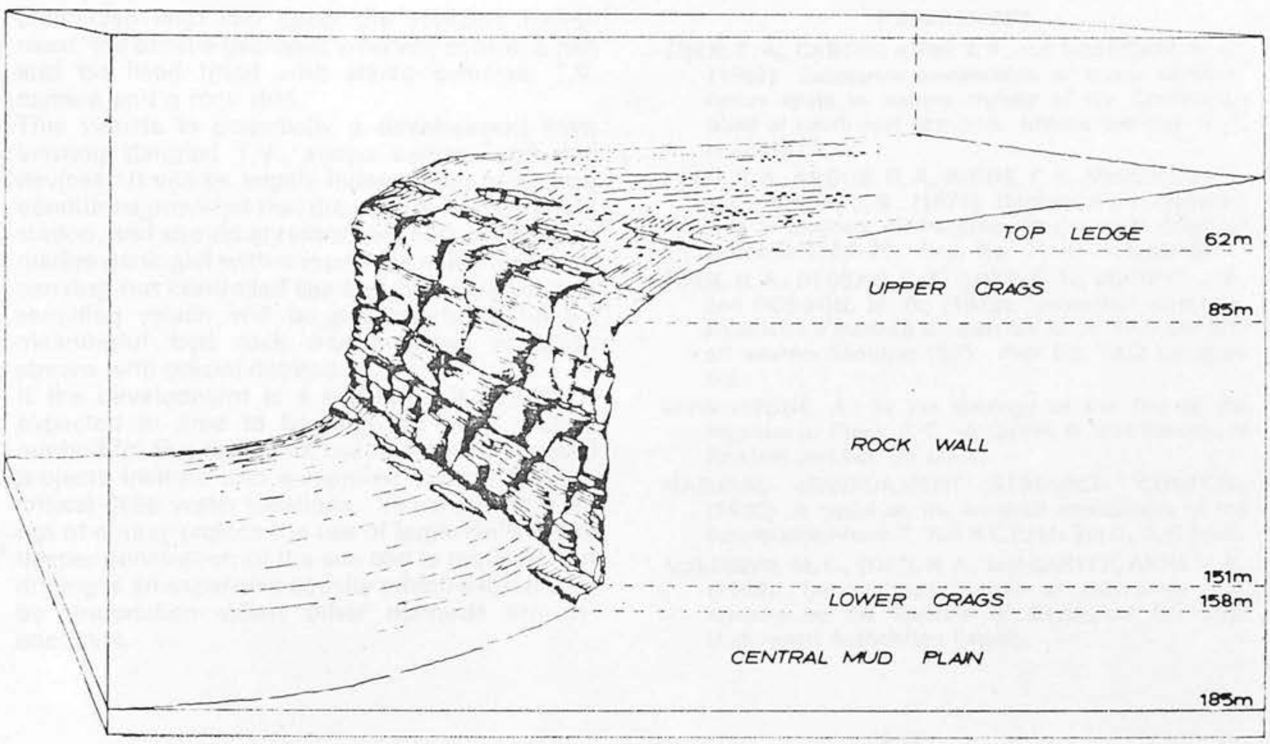


*Figure* 2. Artist's impression of the rock wall on the north-east side of Lower Loch Fyne. True-to-scale drawing compiled by G. A. Goodlet from photographs and descriptions obtained from the submersible Vickers Pisces.

obtaining reliable rock samples either from boreholes or from sea bed exposures. In the I.G.S. 1971 Pisces programme solid rock samples were obtained from eight rock exposures examined in the course of 13 dives in seven days. In money terms this compares favourably with the cost of drilling eight boreholes with the I.G.S./ Wimpey over-the-side drilling vessel M.V. *Whitethorn.*

Study of sea bed geology in the glaciated area surrounding much of the British Isles requires a range of methods, of which the most economical or practical is brought into use at each location. Vickers Pisces is regarded as having proved itself for (1) examination of type localities from which conclusions can be extrapolated and (2) sampling the solid rock forming vertical cliffs and pavements encumbered with erratics. A geologist in Pisces can operate with much the same sort of ease as a free swimming diving geologist, but with a greater duration and capability. With minimal special training many geologists of the I.G.S. marine groups and those working with them have been able to obtain first hand knowledge of the subject of their studies. Experience has, however, indicated that advance practice of the techniques of rapid appraisal and full recording is very well worth while. There is so much to be seen that a practiced operator should be able to keep up a continucus stream of visual records and audio notes, in order that a dive can be fully reconstructed in the course of de-briefing.

## UNMANNED SUBMERSIBLES

Many facets of the sea bed environments summarised above can be investigated by existing remote methods of grabbing, coring, photography or closed circuit T.V. Studying the sea bed by dangling equipment below a ship is, however, rather like trying to study the land surface by dangling instruments from a drifting airship in a fog. Remote controlled equipment at present operationally available to I.G.S. shows excellent but rather disjointed pictures, and there is little scope to investigate features in depth by navigating round and over them. Work with dangled T.V. and drills is particularly difficult when the mother ship is moving up and down in a swell, and there is therefore a severe weather constraint.

There is clearly scope for a more sophisticated unmanned sampling and observation submersible than anything which has so far been seen in the U.K. I.G.S. and the Department of Trade and Industry have therefore commissioned with the British Aircraft Corporation first a design study, and more recently a construction contract, for a vehicle which is required to be moderately priced and with reasonable manoeuverability within a limited area. The device under construction is expected to be able to take over some of the geological functions of Pisces, but is unlikely to displace it for work on difficult sites. It will be cable controlled by two operators stationed at a console aboard a mother ship; one will be a technician who will direct the vehicle's movement, the other a geologist who will control a pan and tilt head fitted with stereo cameras, T.V. camera and a rock drill.

This vehicle is essentially a development from existing dangled T.V., stereo camera and drill devices. It will be largely independent of surface conditions provided that the mother ship can hold station, and should at reasonable cost provide the marine geologist with a round the clock means of carrying out controlled sea bed observations and sampling which will be particularly useful for meaningful bed rock investigations in areas strewn with glacial detritus.

If the development is a success this vehicle is expected in time to become the main routine method for this task, with use of divers on special projects inshore and a manned submersible on critical deep water locations. Visual methods do not of course replace the use of larger drills when deeper penetration of the sea bed is required, but drilling is an expensive activity which should only be undertaken when other methods are inadequate.

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# Glacial and postglacial sedimentation in the Sea of the Hebrides

SHALLOW seismic profiling, sediment coring and drilling from an anchored ship have provided new information about sedimentation in the Sea of the Hebrides. Some initial results are summarized here.

On shallow seismic profiles over the inner continental shelf (east of 08°00′W, Fig. 1) a principal reflector, coincident with a stratigraphic unconformity, is interpreted as a rockhead reflection. This surface is obviously glaciated[1], overdeepened trenches are common, and where it crops out it is smoothed and striated[2]. The layer above this reflector is, therefore, interpreted as Quaternary sediment. Its thickness has been calculated assuming a seismic velocity of 1.8 km $s^{-1}$ and isopachytes are shown in Fig. 1. Cores and boreholes through this layer have recovered the following lithologies.

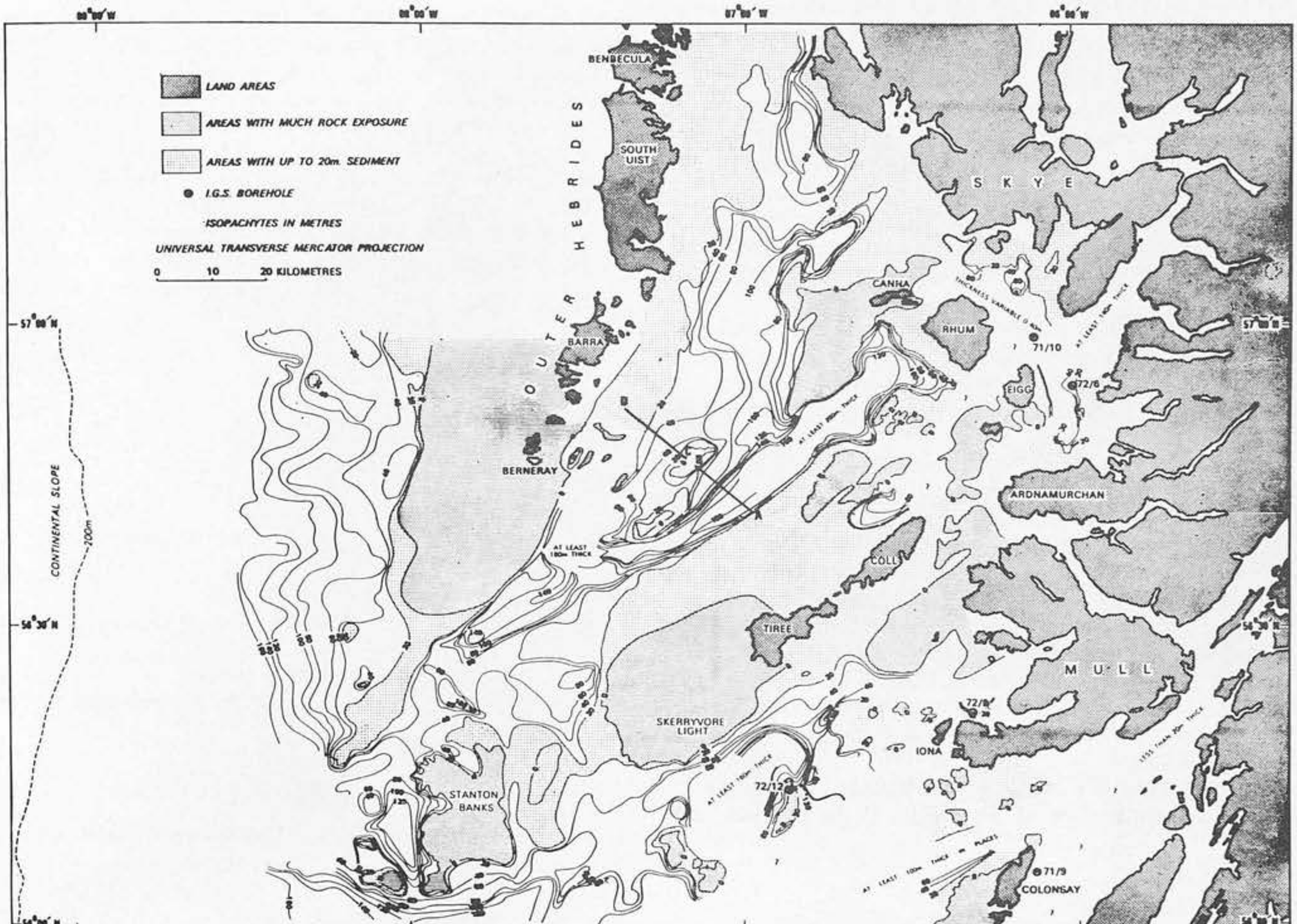


FIG. 1 Isopachytes on Quaternary sediment.

**Formation 1.** Till (Fig. 2) constitutes only a small proportion of the total sediment encountered in the boreholes. Reflections from the surface of moraine hummocks are seen on some seismic profiles (Fig. 3) but more commonly the profiles fail to record a boundary between Formations 1 and 2. This may be due to lack of velocity contrast between the two or to an insignificant thickness of Formation 1.

**Formation 2.** These firm, poorly sorted sandy muds[3] (Fig. 2) contain variable amounts of granule and pebble grade lithic fragments[4]. Benthonic foraminifera are sparse but there is a significant dinoflagellate cyst population.

Lithology (compare with refs 5 and 6), stratigraphical position beneath late glacial sediments of Formation 3 and distribution on the courses of the major ice streams together suggest that Formation 2 was deposited in close association with ice. In spite of the firmness of the sediment and the presence of gravel grade material, the consistently distinctive marine dinoflagellate cyst assemblages indicate that this formation comprises marine sediment and not till. The nature of the 'till' in borehole 72/12 is not understood; it may be a submarine 'flow till'[5] rather than a true till.

**Formation 3.** A pilot study of this formation in borehole 71/9 shows that the sediments are poorly sorted sandy muds[3] similar to Formation 2. They are, however, softer and contain medium sand to pebble grade fragments only rarely, and then at levels coinciding with cold water faunal assemblages.

Study of foraminifera and dinoflagellate cysts has shown that the Formation 3 sequence can be divided into three palaeoclimatic zones[1]. From −30 m to −28 m the foraminiferal population is dominated by *Ammonia batavus* (Hofker), a warm, shallow water species. A rich assemblage of dinoflagellate cysts indicates a similar environment. Between −26 m and −16 m a cold water assemblage of foraminifera, dominated by *Elphidium clavatum* Cushman, coincides with poor recovery of dinoflagellate cysts. From −14 m upwards cold water foraminifera decline in importance. The dinoflagellate cysts from −10 m to the surface are modern in aspect.

The disseminated organic matter contains significant amounts of reworked Mesozoic material. The least contaminated sample was at −6 m; of the organic-walled microplankton only 14.7% were Mesozoic forms and amorphous organic matter appeared fresh. A date of 9,961 ± 250 BP was obtained from the disseminated organic matter at this depth (Scottish Reactor Research Centre 117). This has been taken as a maximum age which reduces to 8,680 BP on the assumption that 14.7% of the carbon is old. Assuming continuous deposition it suggests that the older 'warm' water fauna belongs to the Alleröd interstadial, the 'cold' water fauna to the period of the Loch Lomond readvance stade and the younger 'warm' water fauna to the final climatic amelioration.

Formation 3 sediments are considered to have been deposited at some distance from the ice front (compare with the 'periglacial marine' sediments of southern Alaska[7]). During deposition of the sequence in borehole 71/9, ice, when present, lay behind the present coastline; a plentiful supply of sediment could be expected both from marine erosion of the sea floor and coastline and from fluvio-glacial sources. This would account for the high sedimentation rate implied by the date. A similar succession has been described on the east coast of Scotland (J. D. Peacock, to be published).

The poor recovery of dinoflagellate cysts between −26 m and −16 m may be attributed to a continuously high level of suspended matter (produced by the Loch Lomond readvance stade) and not to low water temperature. The suspended matter would adversely affect the thecate dinoflagellate population and add a dilution factor resulting from high sedimentation rates[8]. In contrast the significant populations of Formation 2 are inferred to have lived in clear, cold water adjacent to floating ice. Potential suspended matter remained frozen into the ice to be released intermittently, perhaps by seasonal melting, to form Formation 2 deposits.

**Formation 4.** These sediments form a thin layer (0.05 m to 2.0 m) on all older formations. Their character can be related to bathymetry and situation with respect to the prevailing south-westerly swell. They are interpreted as modern sediments.

Calibration of shallow seismic profiles by the boreholes suggests that Formations 2 and 3 each produce a characteristic seismic texture which can be used to determine their distribution. Formation 3 typically has closely spaced, horizontal reflectors (Fig. 3) which fade laterally and which cannot be correlated with any visible structure in the boreholes. A second characteristic texture, interpretated as Formation 2, has widely spaced reflectors (Fig. 3). Only borehole 72/12 has passed through this unit but if the interpretation is correct then most of the thick sediments west of Colonsay are of Formation 2, as are those in the trench northwest of Coll (Figs. 1 and 3).

West of Colonsay Formation 3 sediments fill shallow depressions on the surface of Formation 2. In contrast, east of Colonsay, in an area protected from the prevailing south-westerly swell, nearly 30 m of Formation 3 sediments have been deposited and preserved at a topographically higher level (compare boreholes 71/9 and 72/12, Fig. 2). Formation 3 sediments also occur in the trench north-west of Coll (Fig. 3) and in the glacial trenches around the Inner Hebridean islands. Considerable variations in their thickness, however, suggest deposition (or subsequent erosion) under the control of a complex system of currents.

On the outer continental shelf the sea floor is relatively flat but the rockhead reflection drops evenly westwards[1]. There are no trenches overdeepened by glacial action on rockhead and so the possibility that Tertiary sediments lie above it cannot be excluded.

The two seismic textures on profiles west of Colonsay are also present here. Short (0.8 m) cores taken at the outcrop

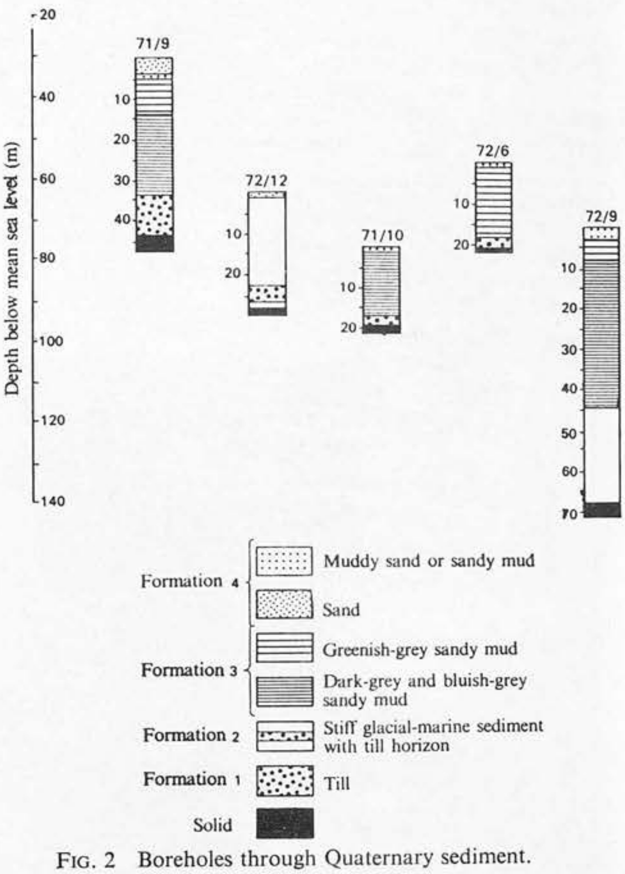


FIG. 2 Boreholes through Quaternary sediment.

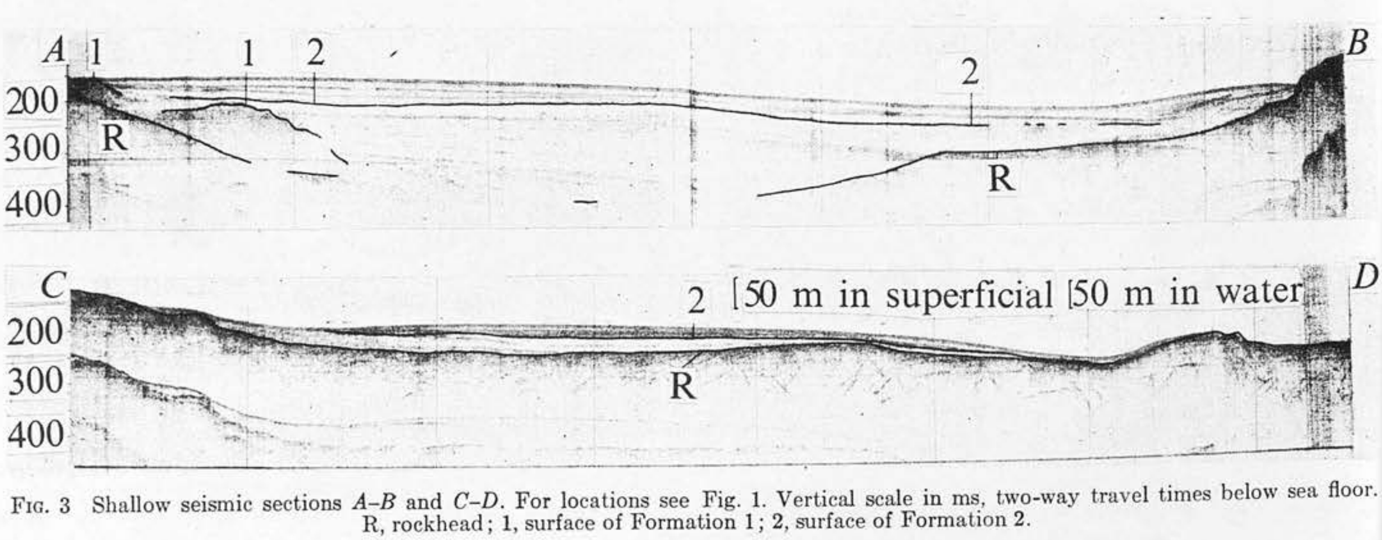


FIG. 3 Shallow seismic sections *A–B* and *C–D*. For locations see Fig. 1. Vertical scale in ms, two-way travel times below sea floor. R, rockhead; 1, surface of Formation 1; 2, surface of Formation 2.

of the lower unit penetrated a thin (0.1 to 0.5 m) cover of Formation 1 sands and gravels to recover Formation 2 sediments.

Evidence from the land shows that a major ice sheet originating on the mainland moved westwards to extend across the outer shelf. In contrast to this evidence, overdeepened trenches off shore trend along north-east to south-west structures[1]. It has been inferred[1] that initially the area was invaded by south-westerly moving ice streams from local high ground, but that during maximum glaciation the westerly moving ice sheet crossed the whole area leaving striae and erratics on areas which are now land. This sequence was reversed during deglaciation.

Deposition of the sediments would have been controlled by the nature of the ice and the manner of its retreat, in particular its relation to changes in sea level. A complex history of sedimentation is thus indicated and the reconnaissance nature of the evidence presented here allows only outline conclusions to be drawn.

It is suggested that the four formations were deposited diachronously by the retreating ice of the last (Devensian) ice sheet. The Formation 2 sediments on the outer continental shelf (Fig. 1) were deposited by the main ice sheet, and those west of Colonsay and north-west of Coll (Figs 1 and 3) by major, south-westerly moving ice streams, probably at a more advanced stage in the retreat. Their thickness reflects the size and activity of the parent glaciers. Formation 3 sediments were deposited at a distance from the ice. When the supply of Formation 3 sediment became exhausted and sea level readjusted to its present position the deposits of Formation 4 were formed.

This study is being undertaken as part of the research programme of the Institute of Geological Sciences.

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*Marine Geology*, 16 (1974): M21–M30


Letter Section

# Helen's Reef: a microgabbroic intrusion in the Rockall intrusive centre, Rockall Bank

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## ABSTRACT

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Rockall Island is composed of 52 ± 9 Ma (m.y.) aegirine granite and forms part of a nearly planated intrusive complex. The nearby Helen's Reef lies within the complex but is composed of Cretaceous (81 ± 3 Ma) microgabbros. The petrography and chemistry of the microgabbros differ from Mid-Ocean Ridge tholeiites but are similar to the Tertiary gabbroic rocks of northwestern Scotland. The relationship of the Cretaceous igneous activity to the evolution of the North Atlantic Ocean is discussed briefly.

## INTRODUCTION

Rockall Island (Fig.1) is the sole subaerial expression of the Rockall Plateau microcontinent (Roberts, 1970; Scrutton, 1972) and is composed of aegirine-granite recently redated at 52 ± 9 Ma (m.y.) (Sabine, 1965; Hawkes et al., 1973). The island forms part of a nearby planated intrusive complex (Roberts, 1969) that is unusual because it is distant from the contemporaneous oceanic crust west of the Rockall Plateau (Vogt et al., 1969) and the Hebridean igneous centres. It has been tacitly assumed that the Rockall Island intrusive complex formed part of the regional volcanism associated with the 60 Ma rifting between Greenland and Rockall Plateau (Vogt et al., 1969) although highly speculative relationships have been sought with possible plume traces on the European plate (Duncan et al., 1972). The petrology and age of rocks from the adjoining intrusive complex are therefore of some regional interest. We report here Cretaceous microgabbros from the nearby Helen's Reef that indicate an earlier and unsuspected phase of igneous activity.

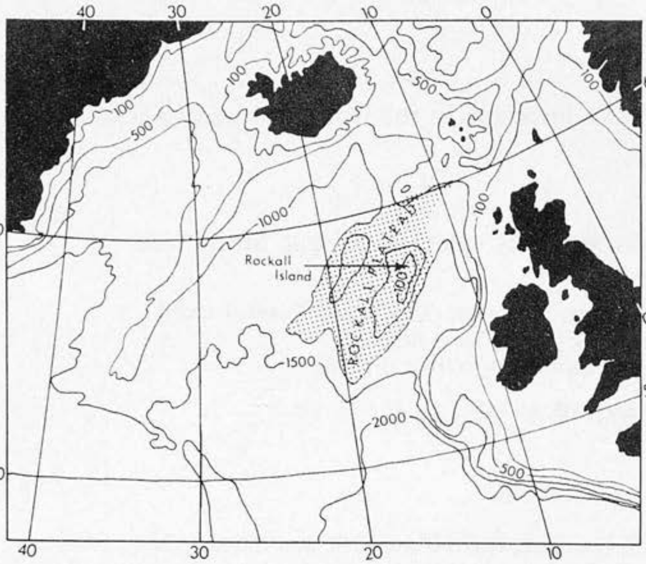


Fig.1. Location of the Rockall Plateau and Rockall Island.

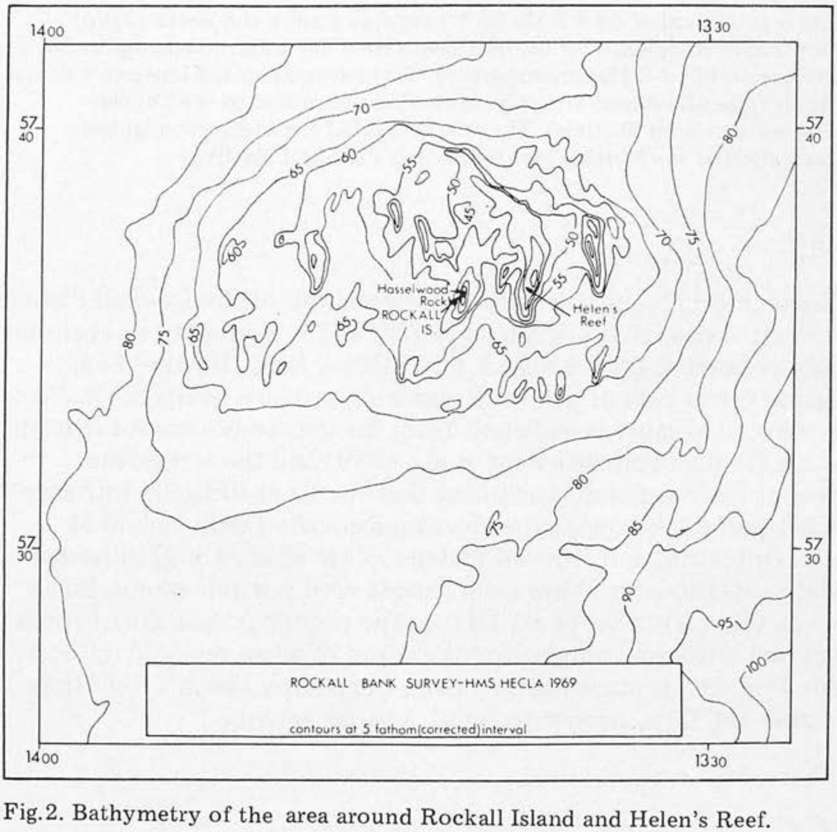


Fig.2. Bathymetry of the area around Rockall Island and Helen's Reef.

## FIELD OBSERVATIONS

Helen's Reef is the tip of a narrow curvilinear shoal rising from 100 m depth located two miles east of Rockall (Fig.2) and associated with a large negative magnetic anomaly (Roberts and Jones, 1973). Echo-sounder traverses across the reef by boats from RFA "Engadine" and visual observations by a team of NIO and IGS divers show that it is the top of a narrow pinnacle breaking surface and rising from a surface of 12 m. This surface is comprised of spurs and buttresses that commonly have steep or vertical, joint-controlled or columnar-jointed faces falling to 20 and 30 m depth. The southeast face is steep and joint-controlled being comparable in this respect to Rockall Island. Both Rockall and Helen's Reef may be resistant stacks formed at a lower sea level (Binns et al., 1973).

The rock samples obtained by the team of Scuba divers over a depth range of 10–17 m (Table I) ranged from chips to 14-cm long blocks adequate for isotopic age determination and chemical analysis.

## RESULTS

The dry samples (Table I) are dark grey (Munsell colour values of N3), with very light grey (N8) speckles in the coarser grained facies. Olivine-microgabbro predominates, with an equigranular (2–3 mm), holo-crystalline, subophitic texture which accounts for its tough and hard nature. No vesicles or amygdales occur. Little-altered, colourless forsterite forms equant crystals, with a composition of $Mg_{1.6}Fe_{0.4}SiO_4$, and pale green to pale brown endiopside — $Ca_{0.9}Mg_{0.9}(Si_{1.9}Al_{0.1})O_6$ are set in a framework of bytownite laths ($Ca_{0.8}Na_{0.2}Al_2Si_2O_8$) averaging $0.8 \times 0.2$ mm. Interstitial anhedral labradorite

TABLE I

List of samples from Helen's Reef, Rockall

| Sample No. | Rock name | Dive No. | Depth (m) | Location |
|---|---|---|---|---|
| S 58556 | olivine-microgabbro | 1 | 10–15 | (a) northern part of reef narrow rock spur |
| S 58557* | olivine-microgabbro | 2 | 10–12 | rock platform |
| S 58563 | troctolite | 3 | 17 | vertical joint-controlled cliff beneath rock platform |
| S 58558 | olivine-microgabbro | 4 | 17 | (b) southern part of reef horizontal ledge |
| S 58562 A* | olivine-microgabbro | | | |
| S 58559-61 | olivine-dolerite | 4 | 17 | on vertical cliff |
| S 58562 B | olivine-dolerite | | | |

*Specimen used for isotopic age determination shows undulatory extinction and no twinning, and is of later crystallization than the laths. The plagioclase is variably paragonitized; similar alteration products mantle the olivine crystals. Chromian magnetite forms dispersed cubes and octahedra, and though a minor constituent, may contribute to the large magnetic anomaly over the reef (Roberts, 1969). The magnetite is unusual in containing up to 13.5% $Cr_2O_3$. Ilmenite occurs as rare anhedral grains.

A finer grained, microporphyritic olivine-dolerite makes a sharp chilled contact with the olivine-microgabbro in samples from the southern part of the reef. In the dolerite, olivine and clinopyroxene microphenocrysts (up to 1 mm across) are set in a strongly fluxioned, fine-grained (0.2 mm) groundmass of ragged pyroxene plates, euhedral colourless forsterite crystals, bytownite laths, and accessory granules of chromian magnetite and ilmenite. The compositions of these minerals are respectively very close to those in the microgabbro.

Local troctolitic cumulates of olivine and pyroxene with subordinate plagioclase occur in samples from the northern part of the reef. They may indicate a degree of gravity settling and thus suggest layered cumulates may occur towards the deeper unexplored base of the reef. Forsterite similar to the above forms segregations of fractured subhedral to euhedral crystals (to 1.4 mm length), commonly mantled by pale green clinopyroxene. The last-named also forms plates poikilitically enclosing bytownite laths, and there is a little accessory chromian magnetite.

Chemical analyses of the olivine-microgabbro and dolerite (Table II) are closely similar. Chlorine was not detected and so little chemical marine weathering has occurred even at the surface of the reef. The more noticeable features are the low total iron contents, low alkalies, high lime and alumina, thus markedly differing from oceanic basalts such as the Mid-Atlantic Ridge tholeiites. There is close agreement, however, with other Tertiary gabbroic rocks (Table II), in particular with an olivine-gabbro sill in Skye that is a member of the Porphyritic Central Magma Series of Mull and Ardnamurchan. The calculated C.I.P.W. norms (Table III) show close agreement for feldspar and olivine (except where chloritized as in the olivine-dolerite, S 58562B). Neither free quartz nor nepheline appear in the norms, the composition representing an undersaturated, non-feldspathoidal magma. Trace elements (Table IV) show a normal range for these rock types, except for chromium, which is anomalously high and accounted for by the chromian magnetite. Rare earths are absent and zirconium low, in contrast to the sodic aegirine-granite of Rockall Island (Hawkes et al., 1973) to which the present rocks bear no direct petrographical or chemical relationship.

The microgabbro has been dated (by N.J. Snelling and C.C. Rundle) by potassium-argon methods on two whole-rock samples, and the analytical data are given in Table V.

The standard deviations shown include errors in the mass-spectrometric measurements, in the spike volume, the error magnification due to the correction for atmospheric argon and errors in the potassium determinations.

TABLE II

TABLE II

Chemical analyses of samples from Helen's Reef, Rockall, and comparative data

| | 1<br>Olivine-microgabbro<br>S 58562 A | 1<br>Olivine-dolerite<br>S 58562 B | 2<br>Ultrabasic feldspars, pyroxene, olivine cumulate, Mullach Bi St Kilda (Harding, 1967) | 3<br>Olivine-gabbro, major intrusion, Cuillins. Coir 'a' Mhadaidh, Skye (Hawker, 1904) |
|---|---|---|---|---|
| $SiO_2$ | 47.00 | 47.10 | 47.76 | 47.28 |
| $Al_2O_3$ | 19.62 | 20.00 | 17.85 | 21.11 |
| $Fe_2O_3$ | 1.10 | 1.00 | 1.53 | 3.52 |
| FeO | 3.66 | 3.44 | 5.62 | 3.91 |
| MgO | 9.87 | 9.84 | 10.17 | 8.06 |
| CaO | 14.65 | 14.89 | 13.51 | 13.42 |
| $Na_2O$ | 1.63 | 1.53 | 1.73 | 1.52 |
| $K_2O$ | 0.05 | 0.04 | 0.03 | 0.29 |
| $H_2O > 105°$ | 1.26 | 1.04 | 0.70 | 0.53 |
| $H_2O < 105°$ | 0.12 | 0.10 | 0.04 | 0.13 |
| $TiO_2$ | 0.34 | 0.33 | 0.25 | 0.28 |
| $P_2O_5$ | 0.02 | 0.02 | 0.02 | tr |
| MnO | 0.08 | 0.08 | 0.13 | 0.15 |
| $CO_2$ | 0.02 | 0.03 | — | — |
| Minor constituents | 0.40 | 0.38 | — | — |
| Totals | 99.82 | 99.82 | 99.34 | 100.20 |

1. Analysts: J.I. Read, J.M. Murphy and G.A. Sergeant, Laboratory of the Government Chemist; 2. analyst: P.R. Harding (1967); 3. analyst: W. Pollard, (in Harker, 1904, p.103).

TABLE III

Modal analyses and norms[1]

| | Modes | | Norms | | | |
|---|---|---|---|---|---|---|
| | olivine-microgabbro S 58562 A (vol. %) | olivine-dolerite S 58562 B (vol. %) | | | olivine-microgabbro S 58562 A (wt. %) | olivine-dolerite S 58562 B (wt. %) |
| Labradorite | 60.0 | 58.5 | ab | F | 13.62 | 13.10 |
| | | | an | | 46.15 | 47.54 |
| Clinopyroxene | 27.5 | 31.0 | di | P | 20.93 | 20.78 |
| | | | hy | | 1.50 | 2.28 |
| Olivine | 12.0 | 6.5 | ol | | 12.95 | 12.18 |
| Chromian, magnetite + ilmenite | tr | tr | nt | M | 1.62 | 1.39 |
| | | | il | | 0.61 | 0.61 |
| Chlorite | tr | 4.0 | | | | |

[1] C.I.P.W.: conventional abbreviations.

TABLE IV

Minor and trace elements in samples from Helen's Reef, Rockall

| | Olivine-microgabbro S 58562 A (p.p.m.) | Olivine-dolerite S 58562 B (p.p.m.) |
|---|---|---|
| Ba* | < 10 | < 10 |
| Co* | 100 | 80 |
| Cr* | 1900 | 1800 |
| Cu* | 31 | 39 |
| Ga* | 13 | 13 |
| Li | < 5 | < 5 |
| Ni* | 370 | 370 |
| Sr* | 260 | 240 |
| V* | 130 | 120 |
| Zr* | < 30 | < 30 |
| B | < 5 | < 5 |
| F | 25 | 30 |
| S | 40 | 20 |

*Optical spectrographic analysis by D.R. Powis; other determinations by J.I. Read, J.M. Murphy and G.A. Sergeant, Laboratory of the Government Chemist.

TABLE V

K-Ar dating of the microgabbro

| Sample no. | % K | Vol. rg$^{40}$Ar. scc/g | % rg | Age and error |
|---|---|---|---|---|
| S 58562 | 0.063 | $2.455 \times 10^{-7}$ | 21 | 95 ± 4 |
| S 58562 | 0.063 | $2.983 \times 10^{-7}$ | 22 | 114 ± 4 |
| S 58557 | 0.106 | $3.397 \times 10^{-7}$ | 24 | 79 ± 3 |
| S 58557 | 0.106 | $3.588 \times 10^{-7}$ | 24 | 83 ± 3 |

Decay constants = $0.585.10^{-10}$ yr., = $4.72 \times 10^{-10}$ yr.

The major errors are in the spike volume and the K determinations. The poor reproducibility given by the first sample (S 58562) may be due to sampling error related to the very low K content. Reproducibility in the second sample (S 58557) is good and indicates a Late Cretaceous age (81 ± 3 Ma). Both rocks give ages significantly older than those of the British Tertiary Province. Although the possibility of excess argon-40 cannot entirely be eliminated, it is considered most improbable in view of the exceptionally fresh state of the rock. Records of excess $^{40}$Ar include chilled, glassy deep-sea basalts (the excess Ar being trapped by rapid cooling), contaminated basalts in the Auckland Volcanic Province (McDougall et al., 1969), and dolerites of the Guyana Shield in which excess argon is attributed to a subsequent metamorphic event resulting in partial or complete resetting of mica ages in the underlying basement (Hebedon et al., 1972). While contamination of the present microgabbros during emplacement cannot be ruled out, no evidence was visible on site nor microscopically in the samples. Further, these contain no glass and do not show any other signs of rapid cooling. A Tertiary regional metamorphism affecting the crustal basement rocks in the area of Helen's Reef seems highly unlikely.

## DISCUSSION

Thus, the available evidence strongly supports a Middle to Late Cretaceous emplacement of the microgabbros, and though this differs significantly from the Tertiary age 52 ± 9 of Rockall Island (Hawkes et al., 1969), there are no firm grounds for assuming the new ages to be anomalous, although further sampling is clearly desirable. As an alternative, we have considered the possibility of an ice-rafted origin but have rejected it for the following reasons:

(1) the microgabbros were sampled at three locations over a depth range of 10—17 m and a distance of 300 m, and are chemically, chronologically and petrologically homogeneous;

(2) all samples were broken off at outcrop by geologist divers who did not observe shattering or sample loose material;

(3) the effects of severe swell at this exposed location would transport downslope any loose material in the 10—17 m depth range;

(4) the basic rocks of Helen's Reef coincide with the large negative magnetic anomaly encircling Rockall Island (Roberts, 1969; Roberts and Jones, 1973).

It is improbable that the whole of Helen's Reef is an enormous glacial erratic measuring some kilometres in length and width (Fig.2), because the plough marks associated with the massive icebergs required to transport such an erratic would be confined to depths exceeding 200 m (Belderson et al., 1973) and the base of Helen's Reef also lies above the outcrop of Flandrian beach conglomerate dredged further south (Roberts et al., 1972).

Since the microgabbros are almost certainly in situ, we have to reconcile their age with the Mesozoic and Tertiary tectonics of the North Atlantic Ocean and also with the 52 ± 9 Ma aegirine-granite of Rockall and the pre-Upper Palaeocene lavas drilled by JOIDES (Laughton and Berggren, 1972). The age of Rockall is closely similar to the age of igneous activity in northwest Scotland (Evans et al., 1973), Greenland (Haller, 1969; Parke et al., 1971) and the Faeroes (Tarling and Gale, 1968). The pattern of Tertiary igneous activity in these areas has been linked with the 60 Ma initiation of spreading between Greenland and the Eurasian plate. However, Rockall is distant from both contemporaneous ocean crust (Vogt et al., 1971; Roberts, 1973) west of Rockall Plateau and the Scottish igneous centres. Although the aegirine-granite may well have been localized by the Cretaceous intrusives, its position within the hinterland of the plate implies regional stress and heating of the Rockall Plateau to permit intrusion some 60 Ma ago.

The Cretaceous igneous activity may be related to either of the two earlier spreading phases that have contributed to the isolation of the Rockall Plateau microcontinent. The earliest of these opened the Rockall Trough and may be Triassic in age (Bott and Watts, 1971) though a Middle to Early Cretaceous age is more probable (Roberts, 1973). The second phase began at about 80 Ma and opened the Labrador Sea by spreading the Greenland-Rockall plate away from North America (Le Pichon et al., 1972; Laughton and Berggren, 1972). A correlation with the latter phase is plausible although there do not appear to be contemporaneous igneous rocks on the margins of the Labrador Sea where the oldest exposed Cretaceous strata have a younger, Turonian age (Rosenkrantz et al., 1969). The position of the microgabbros on the west margin of the Rockall Trough suggests their intrusion may be related to the opening of the Rockall Trough. Contemporaneous Cretaceous igneous activity on the northeast Atlantic continental margin is uncommon but occurs around in the Bay of Biscay where it is recorded in northern Spain (Feuillé and Rat, 1971) and an early stage may be represented by the 134 ± 2 Ma Wolf rock phonolite (Cowperthwaite et al., 1972) in the English Channel. This widely dispersed Cretaceous igneous activity may be related to the early opening of the North Atlantic Ocean and in particular to the contemporaneous (?) formation of the Rockall Trough and Bay of Biscay (Roberts, 1973).

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Table 2. Summary of main structural events.

| SYSTEM | | MAJOR STRATIGRAPHICAL BREAK | MARINE TRANSGRESSION | FOLDING | IGNEOUS ACTIVITY | FAULT MOVEMENT | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Minch Fault | Camasunary-Skerryvore Fault | Great Glen Fault | Other Faults |
| PALAEOGENE | ? | ? | | ?? | | ? | ? | ? | ? |
| | ? | | | ? Gentle folding of lavas/tilting of fault blocks | | E. of Pabbay | On Raasay & E. of Coll | ? Mull | Block faulting of Skye lavas N.W.faults |
| | | | | | | ? | ? | ? | ? |
| | EOCENE | | | ? | ? | | | | |
| | | | | Folding associated with intrusions | Dyke swarms. Plutonic centres. Sills. Lavas | | | | |
| | | ? | | ? | ? | | | | |
| | PALAEOCENE | | | | | ? | ? | ? | |
| CRETACEOUS | UPPER | | ↑ ↑ | | | | | | |
| | LOWER | | | | | ? ? ? | ? | ? | |
| JURASSIC | UPPER | | ↑ | | | | ? | ? | |
| | MIDDLE | | | | | | | ? | |
| | LOWER | | ↑ | | | | | | |
| TRIASSIC | | | | | | ? | ? | ? | ? ? |
| | | | | | | Syn-depositional movement | | | |
| PERMIAN | | ? | | | | ? | ? | ? | ? |
| | | ? | | | | | | | |

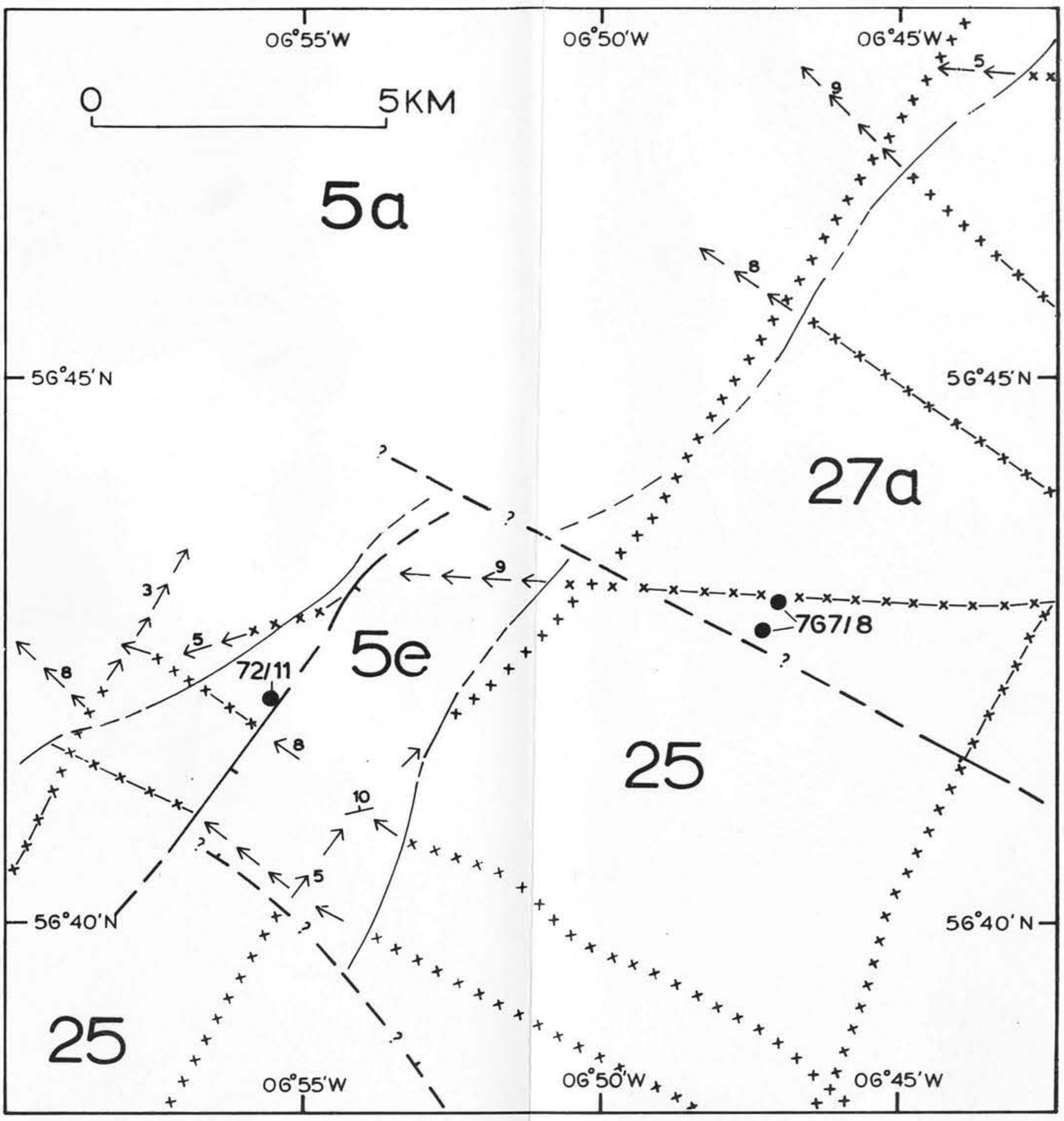
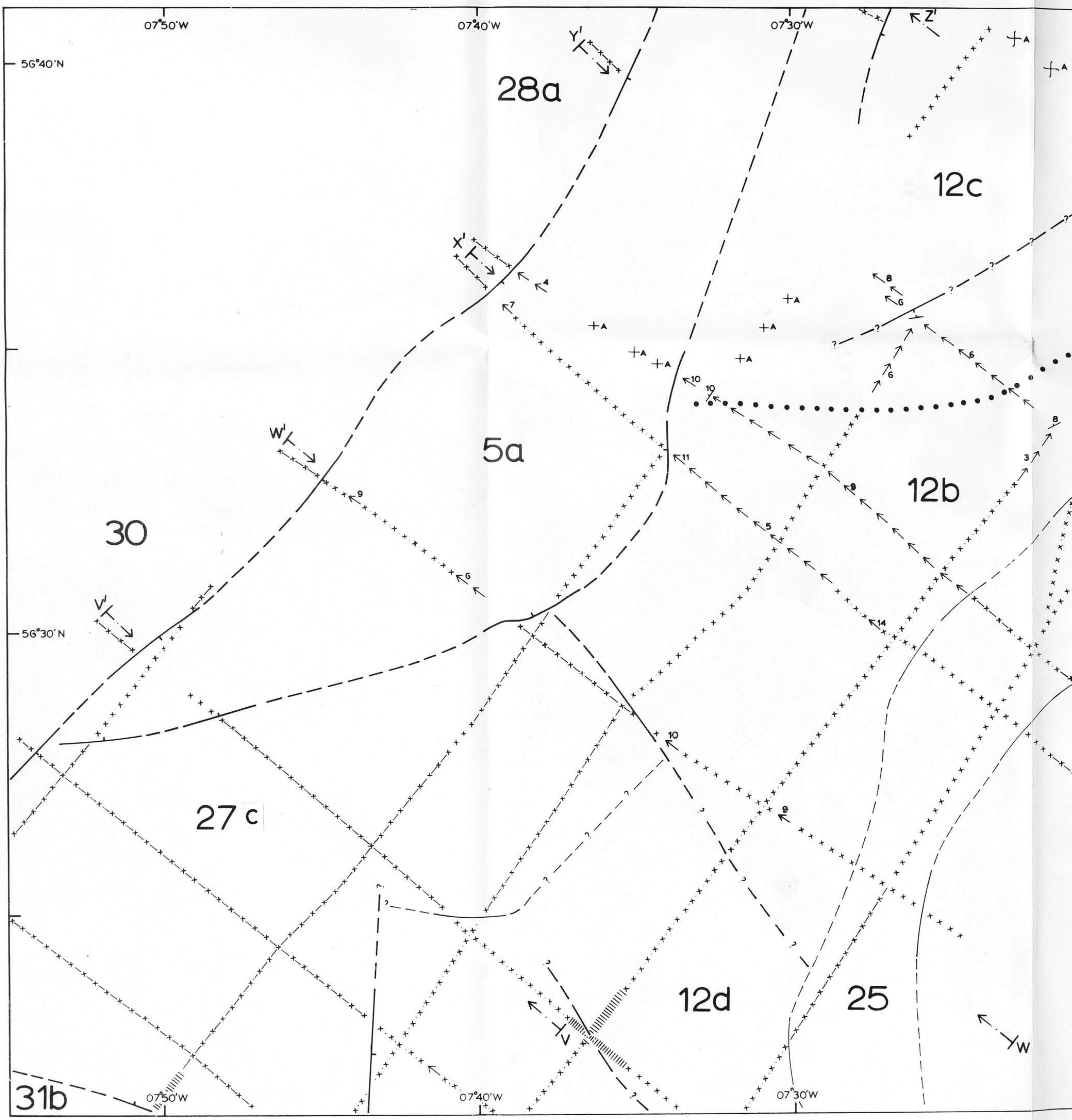



Fig.19b. Shallow seismic evidence in area 2. For location see Fig.5.

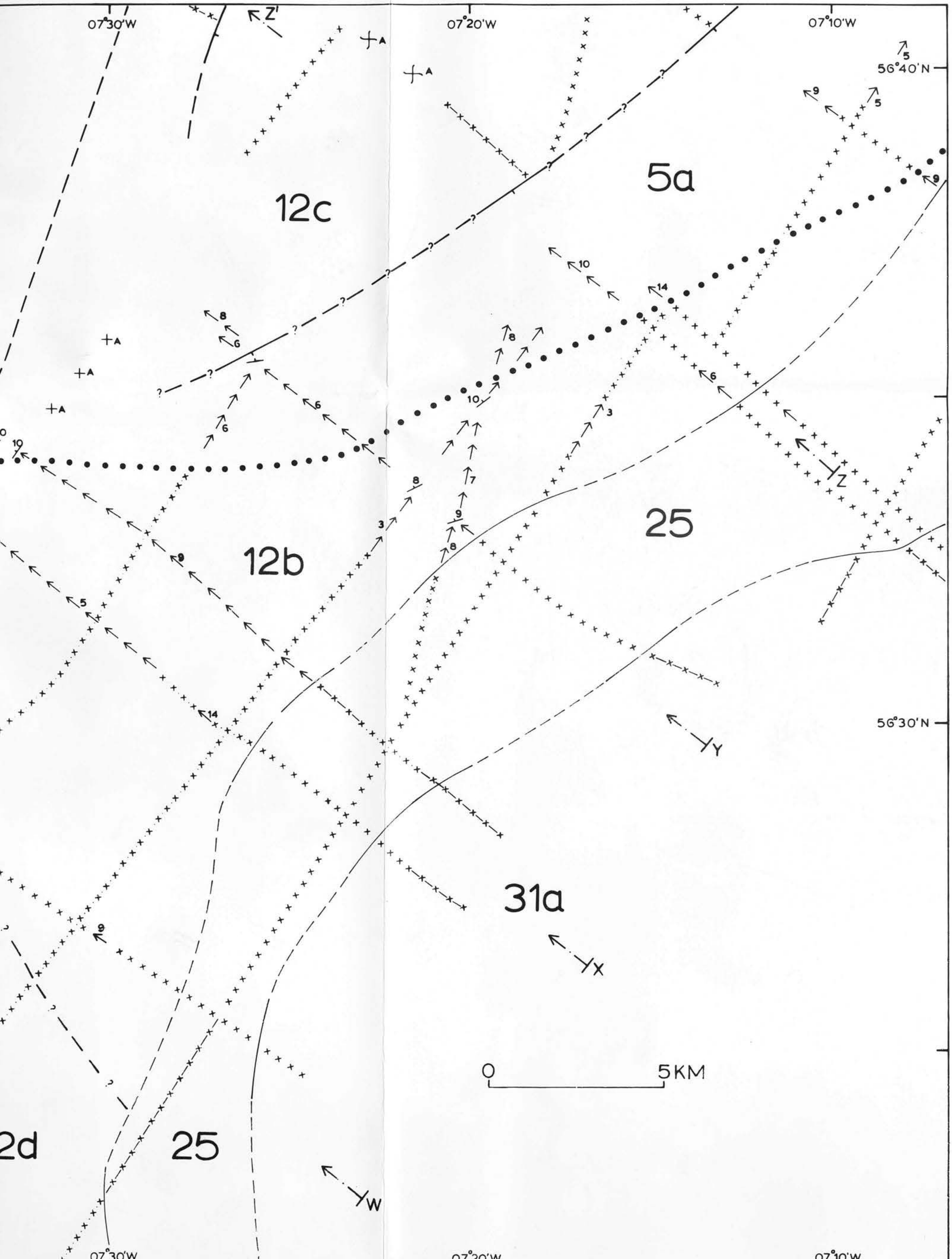
# EXPLANATION

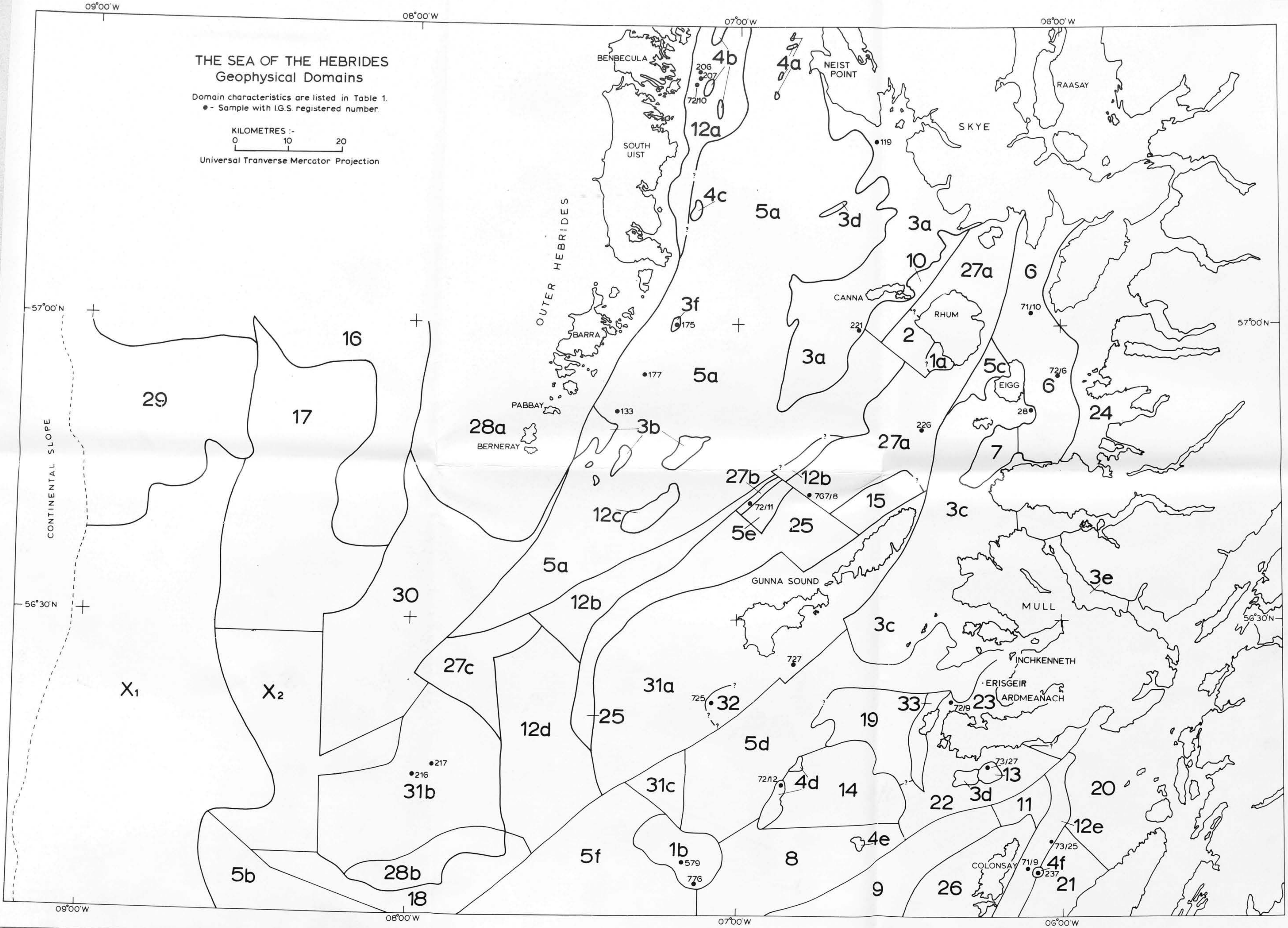
| | |
|---|---|
| x—x—x—x | Rockhead surface uneven and topographically high. |
| x·x·x·x·x | Rockhead surface smooth and topographically low. |
| xxxxxx | Rockhead surface undifferentiated. |
| $\xrightarrow{3}$ | Apparent dip in degrees along seismic profile. |
| +A | Strata apparently horizontal along seismic profile. |
| IIIIIII | Zone of dislocation. |
| 3 | True dip calculated at intersection of seismic profiles. |
| | Fault interpreted from seismic and magnetic profiles. |
| — | Boundary interpreted from seismic and magnetic profiles. |
| ●133 | Sample with IGS registered number |
| ●●●A●● | Prominent scarp on rockhead. |
| 5a | Geophysical domain (see Table 1). |
| V V' | Line of section (see figure 20). |

Fig.19a. Shallow seismic evidence in area 1. For location see Fig.5.



c evidence in area 1. For location see Fig.5.




THE SEA OF THE HEBRIDES
Geophysical Domains
Domain characteristics are listed in Table 1.
• - Sample with I.G.S. registered number.
KILOMETRES :-
0
10
20
Universal Tranverse Mercator Projection
09°00'W
08°00'W
07°00'W
06°00'W
57°00'N
56°30'N
CONTINENTAL SLOPE
OUTER HEBRIDES
BENBECULA
SOUTH UIST
BARRA
PABBAY
BERNERAY
NEIST POINT
SKYE
RAASAY
CANNA
RHUM
EIGG
GUNNA SOUND
MULL
INCHKENNETH
ERISGEIR
ARDMEANACH
COLONSAY
1a
1b
2
3a
3b
3c
3d
3e
3f
4a
4b
4c
4d
4e
4f
5a
5b
5c
5d
5e
5f
6
7
8
9
10
11
12a
12b
12c
12d
12e
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27a
27b
27c
28a
28b
29
30
31a
31b
31c
32
33
X₁
X₂
206
207
72/10
119
175
177
133
221
71/10
72/6
28
226
767/8
72/11
727
725
72/9
73/27
72/12
217
216
579
776
73/25
71/9
237

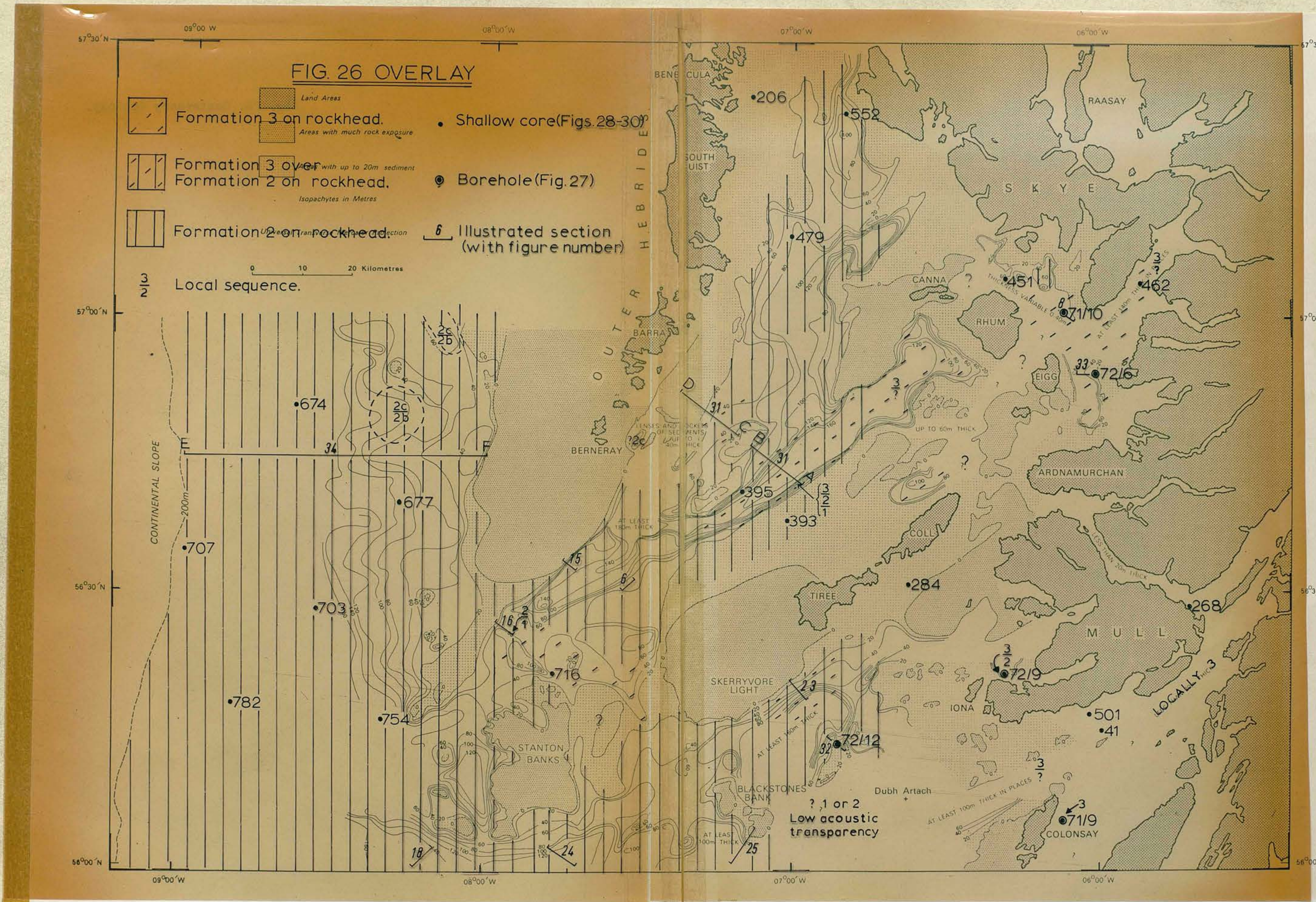



FIG. 26. QUATERNARY GEOLOGY.

BASE - Quaternary sediment isopachyte map (from Binns and others, 1974a).

OVERLAY - Generalised distribution of sedimentary formations 1, 2, and 3. Distribution is based on seismic and borehole (Fig. 27) evidence; Formation 4 and, where it is thin, Formation 3 are therefore not shown.
- Location of shallow cores illustrating Formation 4. (Figs. 28-30)

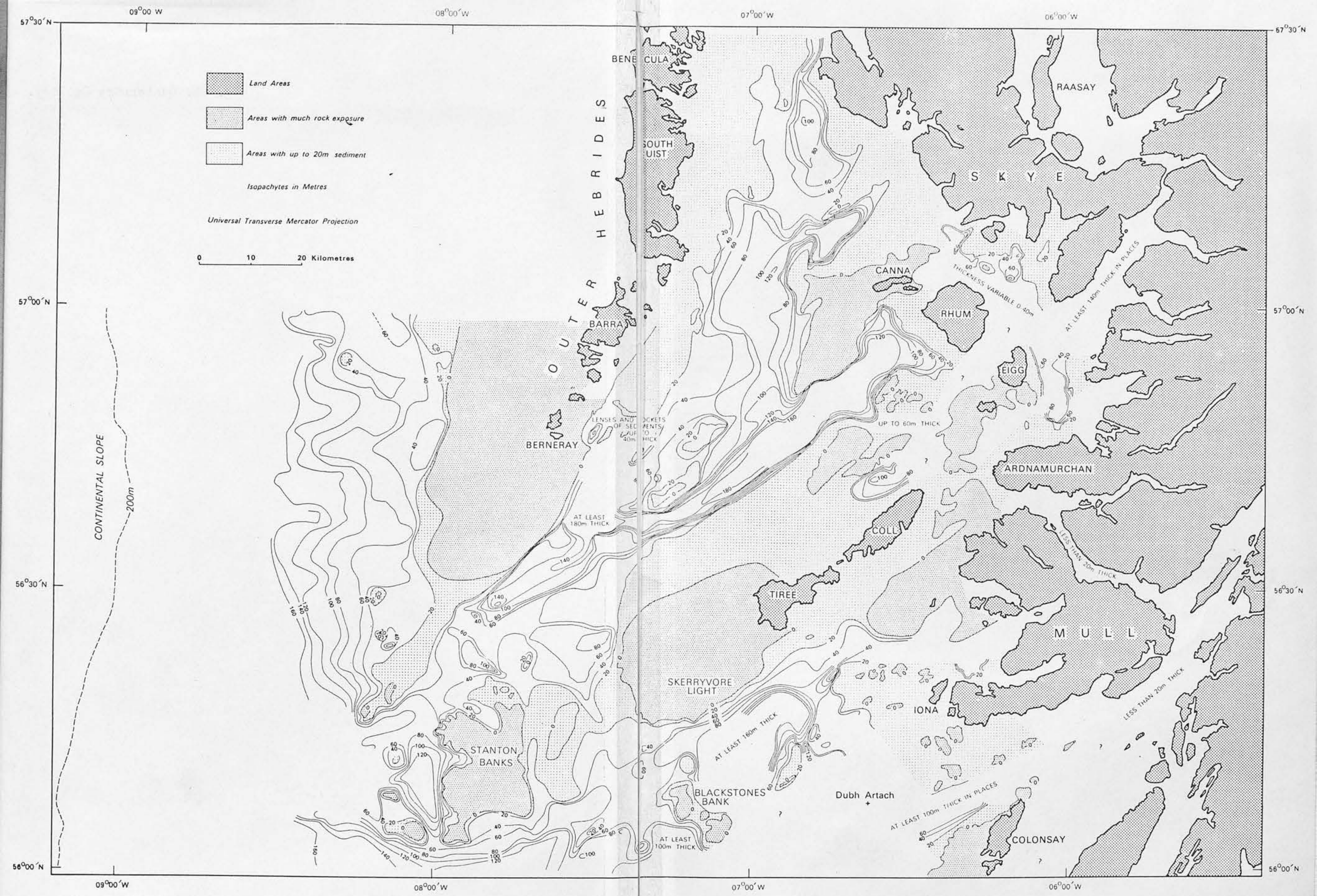



FIG. 26. QUATERNARY GEOLOGY.

BASE - Quaternary sediment isopachyte map (from Binns and others, 1974a).

OVERLAY - Generalised distribution of sedimentary formations 1, 2, and 3. Distribution is based on seismic and borehole (Fig. 27) evidence; Formation 4 and, where it is thin, Formation 3 are therefore not shown.
- Location of shallow cores illustrating Formation 4. (Figs. 28-30)

## TABLE I Interpretation of geophysical domains. For locations see Fig. 9.

| DOMAINS \ EVIDENCE | SHALLOW SEISMIC REFLECTION (REGIONAL MORPHOLOGY) | SHALLOW SEISMIC REFLECTION (STRUCTURE & ROCKHEAD CHARACTER) | AEROMAGNETIC ANOMALIES | SHIPBORNE MAGNETIC ANOMALIES | BOUGUER GRAVITY ANOMALIES | DEEP SEISMIC REFLECTION | BASIS OF INTERPRETATION (Numbers refer to samples) | INTERPRETATION |
|---|---|---|---|---|---|---|---|---|
| 1 (a-b) | Topographic high. | No penetration; surface uneven. | Large anomalies in arcuate form. | High amplitude; short-medium wavelengths. | Very large positive anomalies (>70mgal). | No penetration. | 579, 776; similarity of gravity & aeromagnetic anomalies to those over plutonic centres onshore. | Tertiary plutonic centre (basic igneous) |
| 2 | Topographic high. | No penetration; surface uneven. | | Small | — | — | Continuation onshore. | Tertiary plutonic centre (acid igneous). |
| 3 (a-f) | Topographic high with steep scarps at the margins. | No penetration; surface locally uneven but more commonly even. | Large negative anomalies. | High-moderate amplitude; short-medium wavelength. | No perceptible anomalies. | No penetration. | 28, 119, 175, 221; continuation onshore; Similarity of aeromagnetic anomalies, to those over lavas onshore. | Tertiary basaltic lavas or tuffs. |
| 4 (a-f) | Topographic high. | No penetration; surface uneven; intrusive structure evident. | — | High amplitude; short wavelength. | — | — | 237, 72/12; intrusive structure evident on seismic profiles; magnetic anomaly. | Tertiary hypabyssal rocks. |
| 5 (a-f) | Topographic low; penetration to rockhead locally not achieved. | Good penetration and resolution of rock structure where present; surface smooth. | Low values and smooth gradients. | Small or absent. | Low values (<55mgal). | Good penetration. | 175, 177; Continuation onshore at Neist Point, Skye: seismic character and topography. | Jurassic-Cretaceous sediments. |
| 6 | Topographic high. | Locally poorly developed bedding; surface uneven. | — | Small or absent. | Low, (0-20 mgal) | — | 71/10, 72/6; continuation onshore. | Permo-triassic to Jurassic sediments. |
| 7 | Topographic low. | No penetration; surface uneven. | — | Small and frequent; locally high amplitude, long wavelength. | — | — | Structural position; seismic character. | Permian-Cretaceous sediments intruded by Tertiary igneous rocks of the Ardnamurchan Plutonic Centre. |
| 8 | Topographic low; penetration to rockhead not achieved. | — | — | Generally small, locally of high amplitude. | Intermediate values. | Good penetration. | Topography; magnetic anomalies. | Permian or younger sediments with intrusions. |
| 9 | Topographic low: (penetration to rockhead not achieved) | — | — | Small or absent. | Low <15mgal. | Good penetration. | Topography, gravity and magnetic anomalies. | Permian or younger sediments. |
| 10 | Topographic low. | Apparently structureless; surface even. | — | Small or absent. | — | — | Topography and structural position. | Permian-Cretaceous sediments. |
| 11 | Topographic low. | Apparently structureless; surface moderately even or uneven. | — | — | Low <10mgal. | — | Topography and structural position. | Permian-Jurassic sediments. |
| 12 (a-e) | Topographic high. | Locally poorly developed bedding (some good bedding in b); surface moderately even or uneven. | — | Small or absent. | — | Penetration to acoustic basement. | 71/9, 72/10, 73/25, 206, 207. Structural position. | Permian-lower Jurassic sediments. |
| 13 | Topographic low. | Bedding, even surface. | — | Small or absent. | — | — | 73/27 | Area with locally downfaulted Permo-triassic sediments. |
| 14 | | Dips >10°; surface moderately even. | Large positive anomaly. | Small or absent. | Intermediate values. | — | Seismic character; magnetic anomalies; structural position. | Late Palaeozoic to Cretaceous sediments. |
| 15 | Topographic low. | Apparently structureless; surface uneven. | Smooth gradient into Domain 27a. | Small or absent. | Intermediate values. | — | Topography; magnetic anomalies. | Permian-Cretaceous sediments. |
| 16 | Topographic low. | Apparently structureless; even or locally uneven. | — | Absent. | Low (35-55mgal). | — | Gravity low; absence of magnetic anomalies, topography; seismic character. | Upper Palaeozoic-Triassic sediments. |
| 17 | Topographic low. | Apparently structureless; even or locally uneven. | — | Small | Low (40-60mgal). | — | As domain 16. | Upper Palaeozoic-Triassic sediments. |
| 18 | Topographic low. | Apparently structureless; even or locally uneven. | — | Small or absent (rockhead at depth). | — | — | Seismic character and structural position. | Torridonian to Upper Palaeozoic sediments. |
| 19 | Topographic high. | Apparently structureless; uneven. | Magnetic low. | Small, locally moderate to high amplitude, medium wavelength. | Intermediate values. | — | Surface morphology and structural position. | Torridonian to Upper Palaeozoic sediments with intrusions. |
| 20 | Complex system of troughs and ridges. | Apparently structureless; uneven surface. | NW-SE anomalies of short wavelength. | Small or absent. | — | — | Seismic and magnetic character; topography; continuation onshore. | Dalradian metasediments, intruded by dykes. |
| 21 | Topographic high with troughs. | Apparently structureless; uneven surface. | Even gradient. | Anomalies weak or absent. | — | — | Seismic and magnetic character, structural position. | Late Pre-Cambrian to Upper Palaeozoic sediments or metasediments. |
| 22 | Topographic high. | No penetration; surface uneven. | — | Small or absent. | Intermediate values. | — | Morphology, islets; continuation onshore. | Moine schist or Caledonian granite. |
| 23 | Topographic high. | No penetration; surface uneven. | — | — | — | — | Islet of Erisgeir; 71/9. | Moine schist. |
| 24 | Topographic high. | No penetration; surface uneven. | — | — | — | — | Continuation onshore. | Moine schist of Morar. |
| 25 | Topographically intermediate. | Locally poorly developed bedding; surface even. | Even gradient. | Small or absent. | — | Penetration but no good reflectors. | Seismic and magnetic character; structural position. | Late Pre-Cambrian to Palaeozoic sediments. |
| 26 | Topographic high. | No penetration; surface uneven. | Even gradient. | Small or absent | High (15-35mgal) | — | Continuation onshore. | Torridonian of Colonsay. |
| 27 (a-e) | Topographic high. | Apparently structureless; surface uneven. | Positive anomalies, (c - Locally has Lewisian character). | Small or absent (rockhead in C may be at depth). | Intermediate values. | | 226, 767, 768, 72/11. Continuation onshore on Rhum, Soay and Skye. | Torridonian sandstone (c may be Lewisian). |
| 28 (a-b) | Topographic high. | No penetration; surface uneven. | Large positive anomalies (data for 31a only) | Moderate—high amplitude; medium—long wavelengths. | High, (>60mgal.). | No penetration. | Continuation on Outer Hebrides. | Pre-Cambrian (Lewisian) gneiss (pyroxene-granulites-McQuillin and Watson, 1973). |
| 29 | Penetration to rockhead not achieved. | — | — | Low-moderate amplitude; long wavelength. | High (>60mgal). | — | Comparison of gravity values with Outer Hebrides. | Pre-Cambrian (Lewisian) gneiss. |
| 30 | Topographic high descending to south-west. | No penetration; surface uneven. | — | Moderate-high amplitude; long wavelength (rockhead at depth in south-west). | Intermediate values. | — | Surface morphology and magnetic anomalies. | Pre-Cambrian (Lewisian) gneiss. |
| 31 (a-c) | Topographic high. | No penetration; surface uneven. | Large positive anomalies (data for 31a and c only). | Moderate-high amplitude; long wavelength. | Intermediate values. | No penetration. | 216, 217, 727, Skerryvore Islet; continuation on Coll and Tiree. | Pre-Cambrian (Lewisian) gneiss(granitic) of Coll and Tiree. |
| 32 | Topographic high. | No penetration; surface even or locally uneven. | — | Extremely high amplitude; very short wavelength. | — | — | 727; Local occurence on Coll and Tiree. | Pre-Cambrian (Lewisian) gneiss with magnetic veins. |
| 33 | Topographic high. | — | Large positive anomalies. | — | Intermediate values. | — | Continuation on Iona. | Pre-Cambrian (Lewisian) gneiss. |
| X1 | Penetration to rockhead not achieved. | — | — | Low amplitude; long wavelength. Locally high amplitude coinciding with the 50mgal gravity ridge. | High (35-60mgal). | — | Insufficient evidence. | Pre-Cambrian or Palaeozoic |
| X2 | Topographic low. | Apparently structureless; surface even or uneven. | — | Variable. | Intermediate values. | — | Insufficient evidence. | ? |

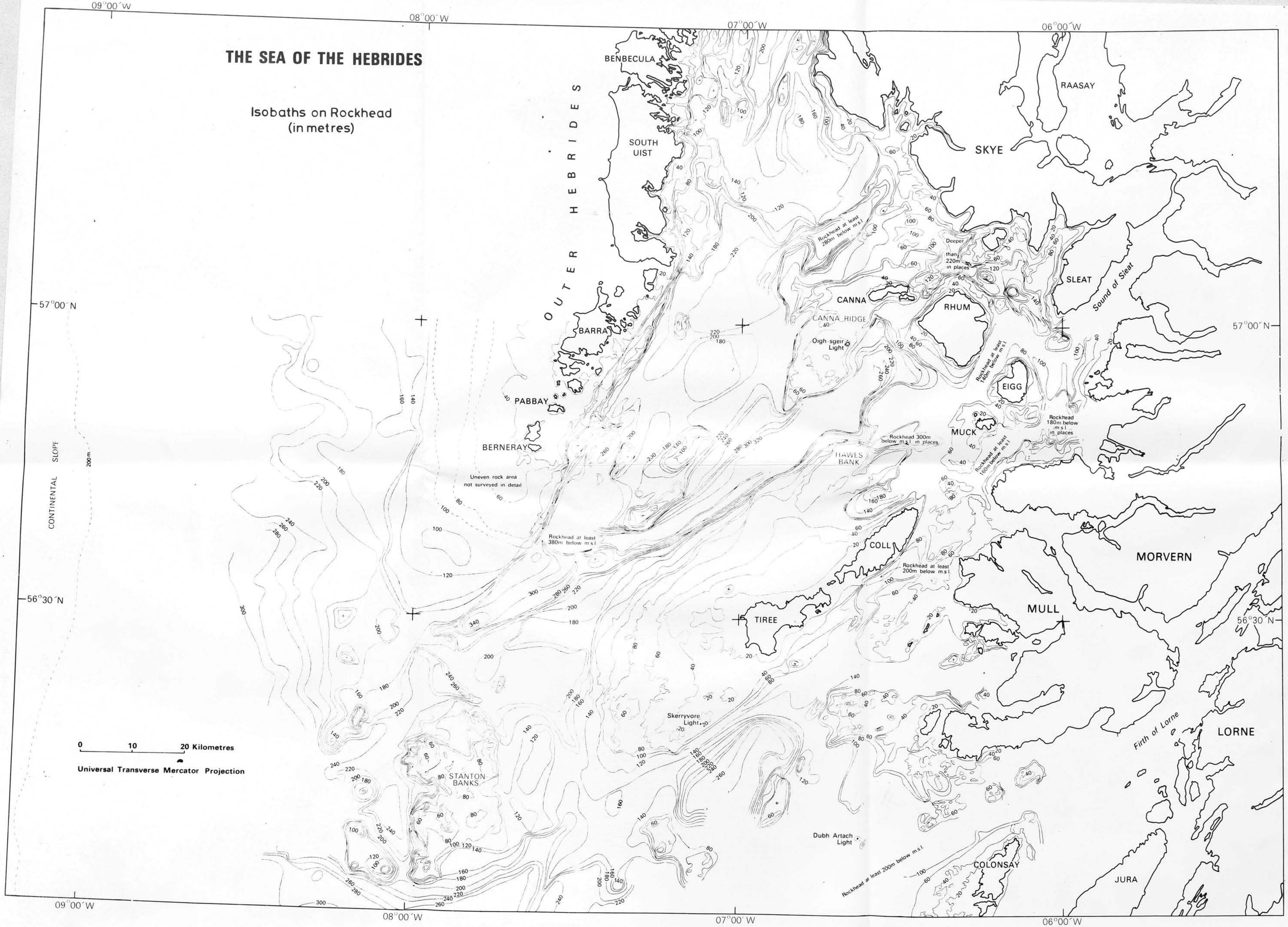
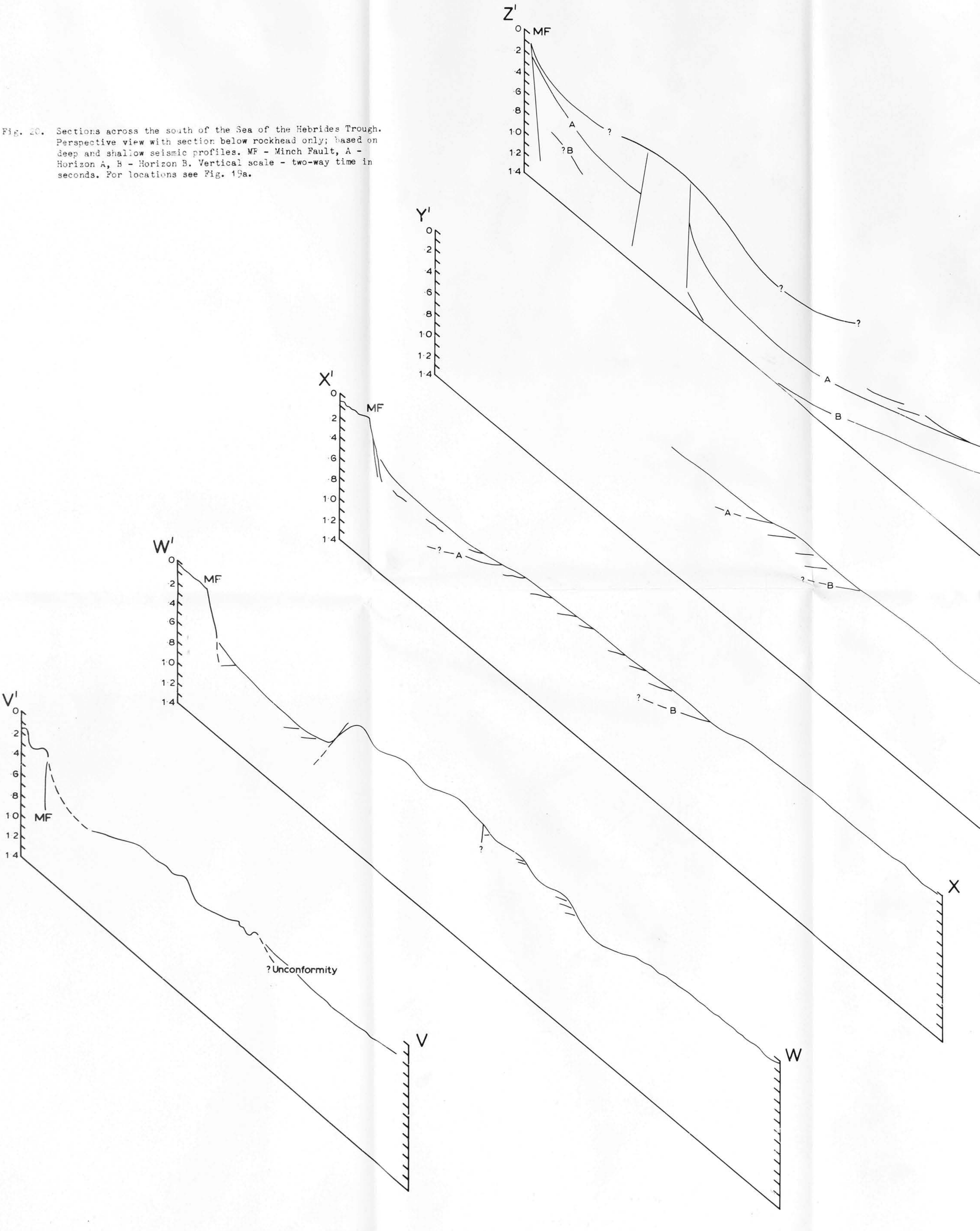
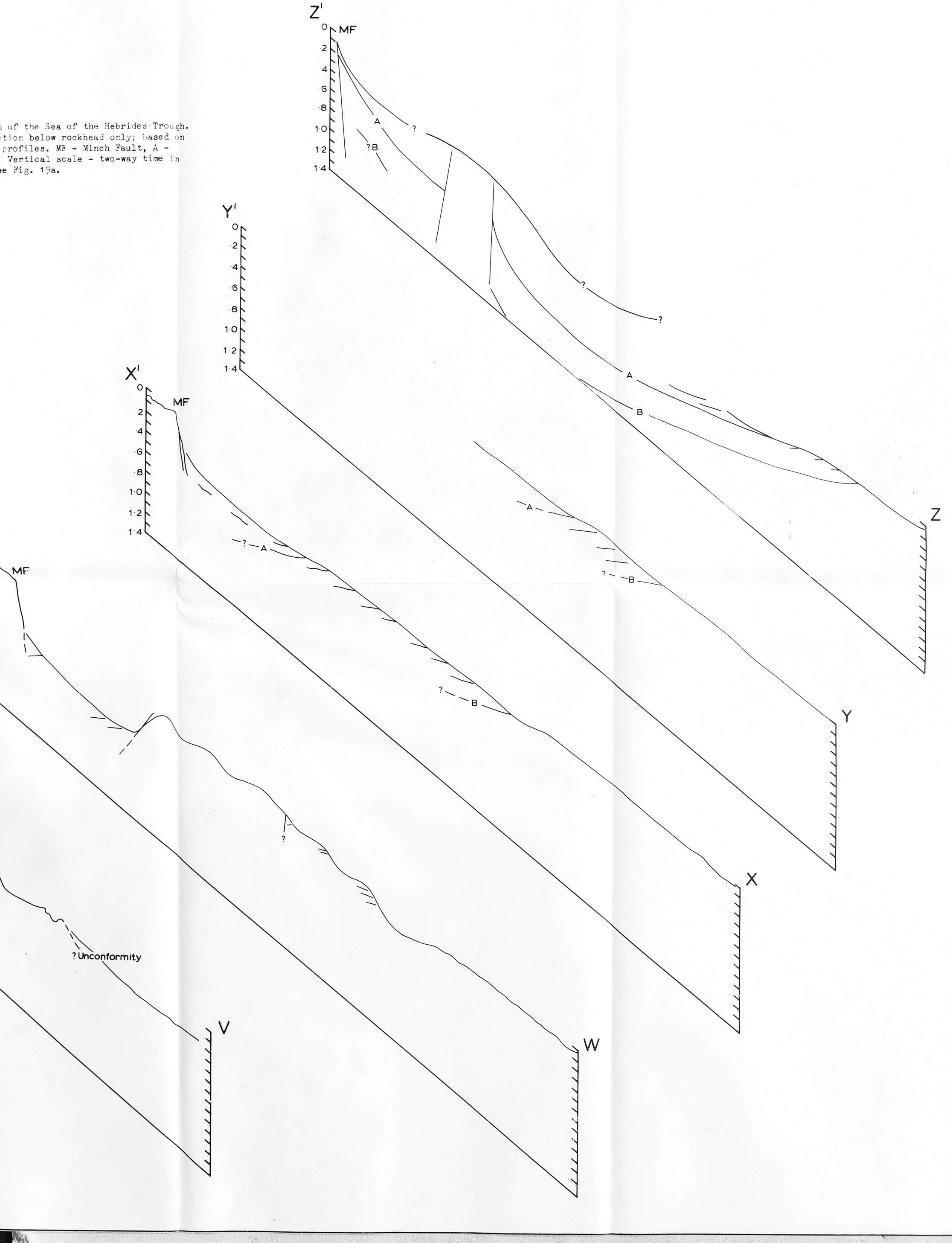
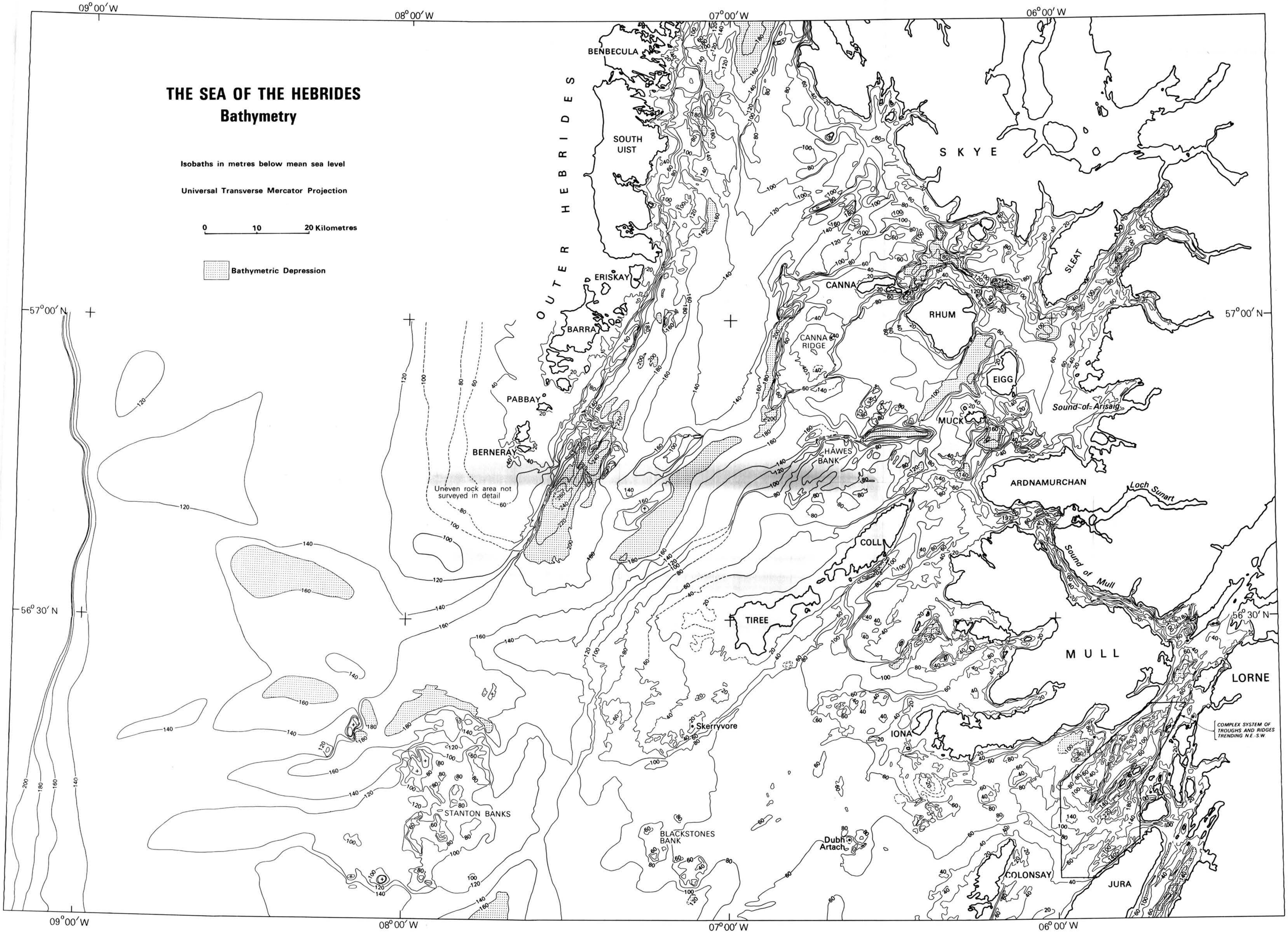

THE SEA OF THE HEBRIDES
Isobaths on Rockhead
(in metres)
09°00´W
08°00´W
07°00´W
06°00´W
57°00´N
56°30´N
BENBECULA
SOUTH UIST
OUTER HEBRIDES
BARRA
PABBAY
BERNERAY
SKYE
RAASAY
SLEAT
Sound of Sleat
CANNA
CANNA RIDGE
Oigh-sgeir Light
RHUM
EIGG
MUCK
HAWES BANK
COLL
TIREE
MULL
MORVERN
LORNE
Firth of Lorne
JURA
COLONSAY
Dubh Artach Light
Skerryvore Light
STANTON BANKS
CONTINENTAL SLOPE
Uneven rock area not surveyed in detail
Rockhead at least 280m below m.s.l.
Deeper than 220m in places
Rockhead at least 140m below m.s.l.
Rockhead 180m below m.s.l. in places
Rockhead 300m below m.s.l. in places
Rockhead at least 160m below m.s.l.
Rockhead at least 380m below m.s.l.
Rockhead at least 200m below m.s.l.
Rockhead at least 200m below m.s.l.
0 10 20 Kilometres
Universal Transverse Mercator Projection

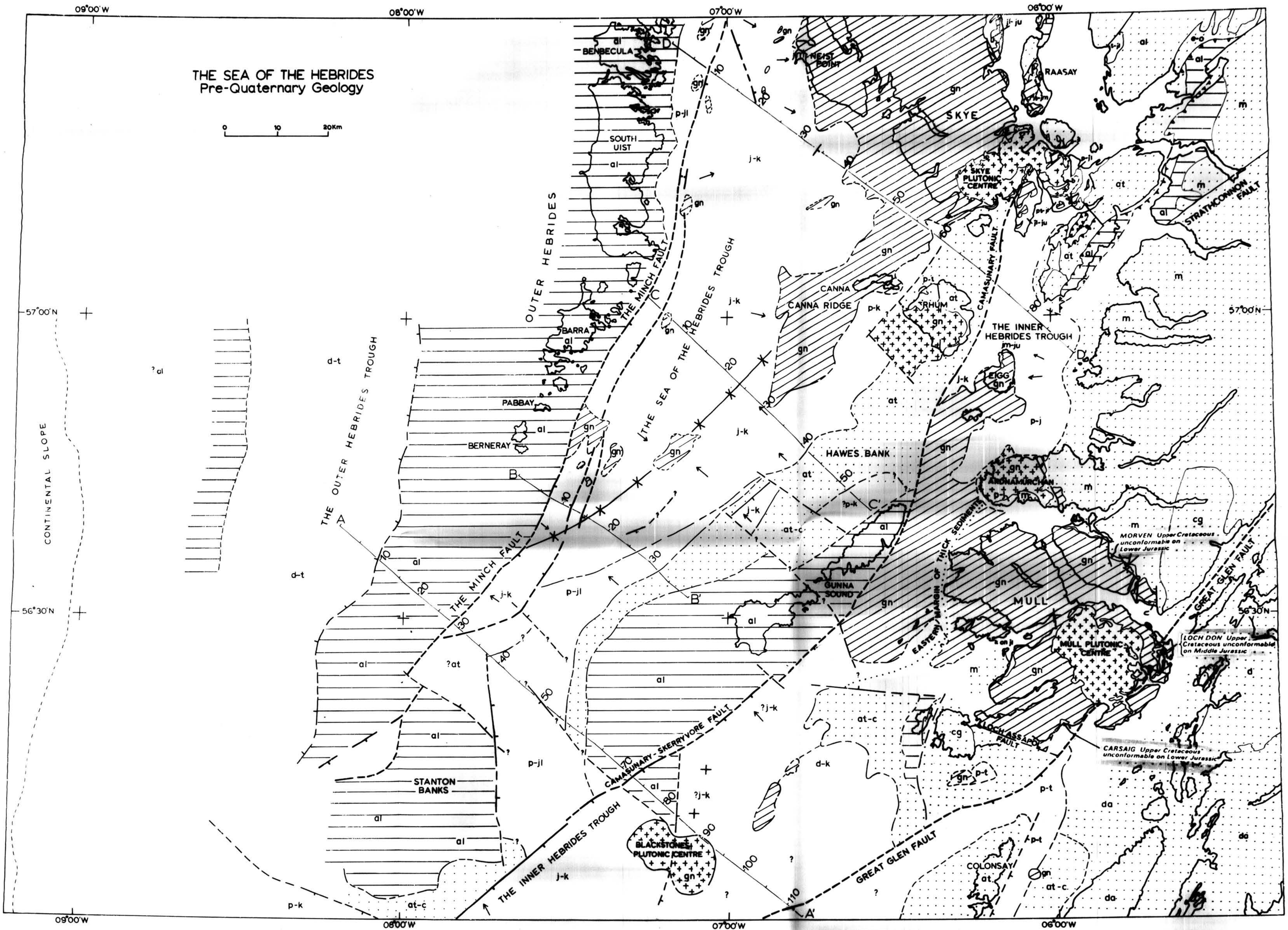
Fig. 20. Sections across the south of the Sea of the Hebrides Trough. Perspective view with section below rockhead only; based on deep and shallow seismic profiles. MF - Minch Fault, A - Horizon A, B - Horizon B. Vertical scale - two-way time in seconds. For locations see Fig. 19a.



n of the Sea of the Hebrides Trough.
ction below rockhead only; based on
profiles. MF - Minch Fault, A -
Vertical scale - two-way time in
ee Fig. 19a.




THE SEA OF THE HEBRIDES
Bathymetry
Isobaths in metres below mean sea level
Universal Transverse Mercator Projection
0 10 20 Kilometres
Bathymetric Depression
09° 00′ W
08° 00′ W
07° 00′ W
06° 00′ W
57° 00′ N
56° 30′ N
BENBECULA
SOUTH UIST
OUTER HEBRIDES
ERISKAY
BARRA
PABBAY
BERNERAY
SKYE
CANNA
RHUM
SLEAT
CANNA RIDGE
EIGG
Sound of Arisaig
MUCK
HAWES BANK
ARDNAMURCHAN
Loch Sunart
Sound of Mull
COLL
TIREE
MULL
LORNE
Uneven rock area not surveyed in detail
Skerryvore
IONA
COMPLEX SYSTEM OF TROUGHS AND RIDGES TRENDING N.E.-S.W.
STANTON BANKS
BLACKSTONES BANK
Dubh Artach
COLONSAY
JURA




# EXPLANATION

gn — Tertiary lavas, sills and minor intrusions.

Tertiary plutonic centres.

Permo-Triassic to Cretaceous sediments (p - Permian, t - Triassic, j - Jurassic, k - Cretaceous; l - Lower, m - Middle, u - Upper).

Late Precambrian and Palaeozoic rocks (at - Torridonian, e-o - Cambro-Ordovician, d - Devonian, c - Carboniferous, da - Dalradian metasediments, m - Moine Schists. cg - Caledonian granite.

al — Precambrian (Lewisian) gneisses.

Geological boundaries, onshore and where observed on marine geophysical profiles.

Geological boundaries, position based on morphology or aeromagnetic maps offshore.

Great Glen, Camasunary-Skerryvore and Minch Faults, position based on morphology or aeromagnetic maps offshore.

Great Glen, Camasunary-Skerryvore and Minch Faults onshore and where observed on marine geophysical profiles.

Other faults, onshore and where observed on marine geophysical profiles.

Other faults, position based on morphology or aeromagnetic maps offshore.

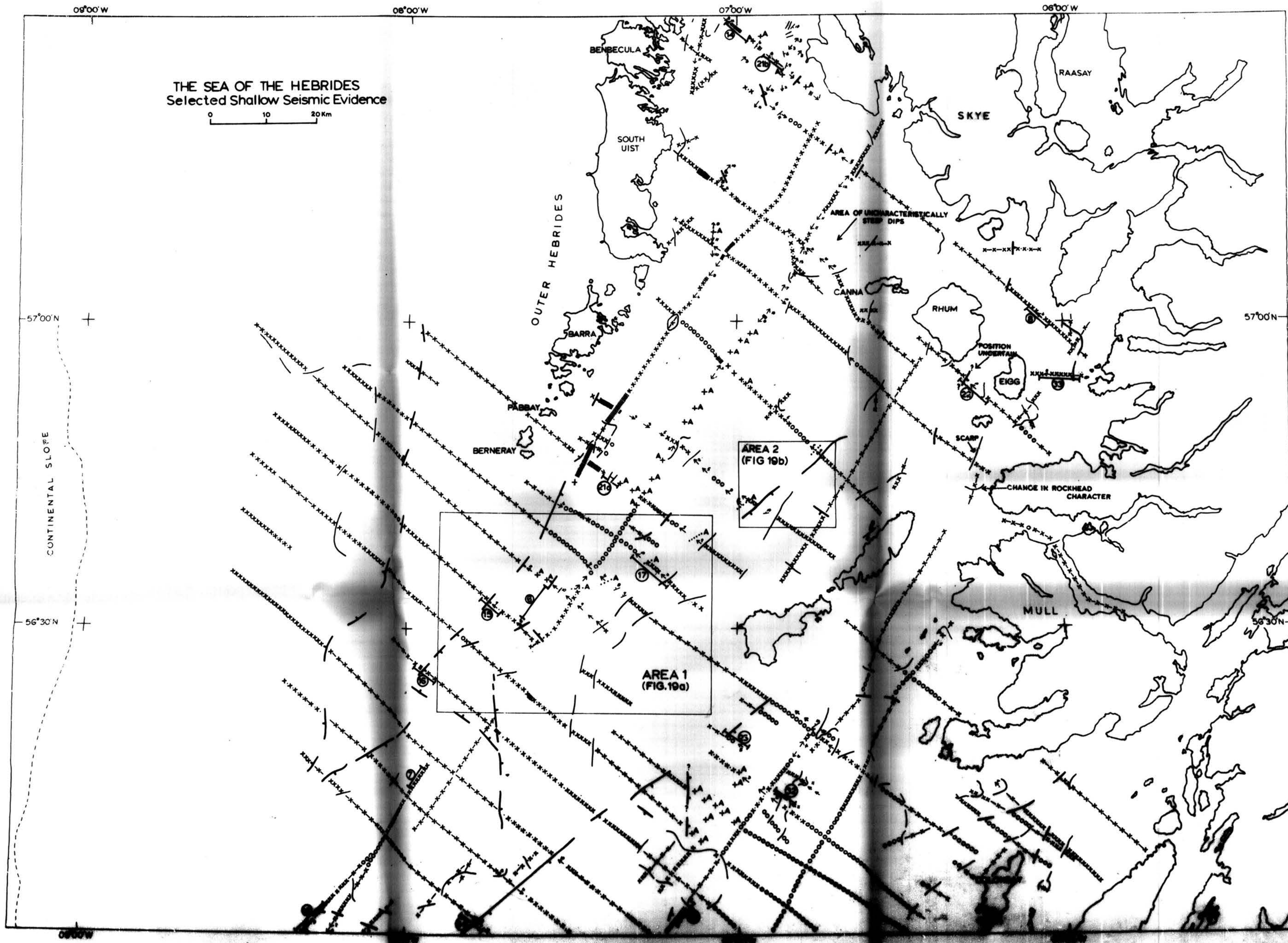
Caledonian thrusts.

General dip of strata.

Strata horizontal

Axis of syncline.

A A' Line of section (Figs. 10-13).




## EXPLANATION

- Rockhead surface uneven and topographically high.
- Rockhead surface smooth and topographically low.
- Rockhead surface undifferentiated.
- Apparent dip in degrees along seismic profile.
- Strata apparently horizontal along seismic profile.
- Zone of dislocation.
- No evidence.
- True dip calculated at intersection of seismic profiles.
- Fault interpreted from seismic and magnetic profiles.
- Boundary interpreted from seismic and magnetic profiles.
- Prominent scarp on rockhead.
- 21 Illustrated section (with figure number).